Variability & Statistical Process Control

Outline

Section 1: Understanding the Impact of Variation

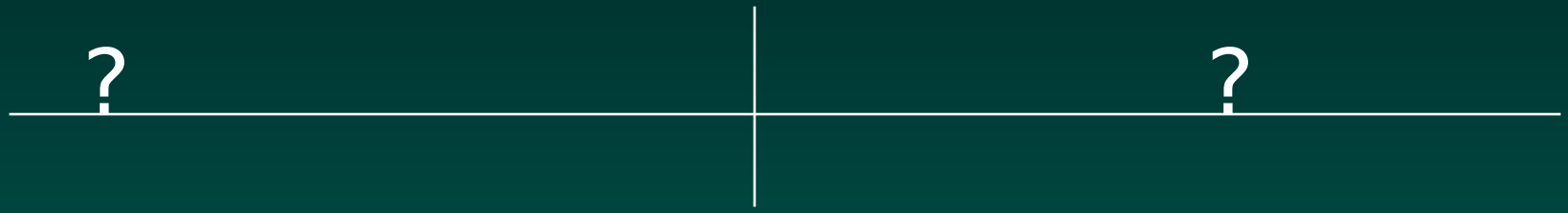
Section 2: Process Control Systems

Section 3: Measurement Capability Analysis

What is Variation?

Loss Function

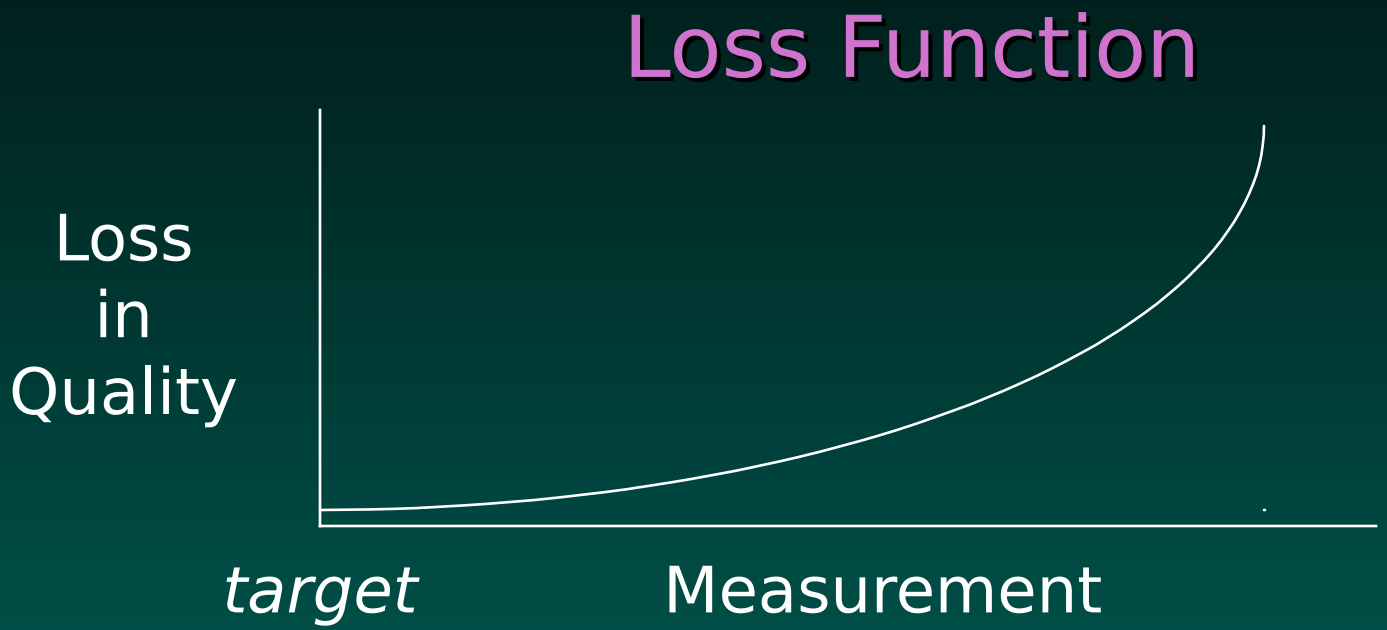
What is the target for a given process?



Target

How far away from the target is still OK?

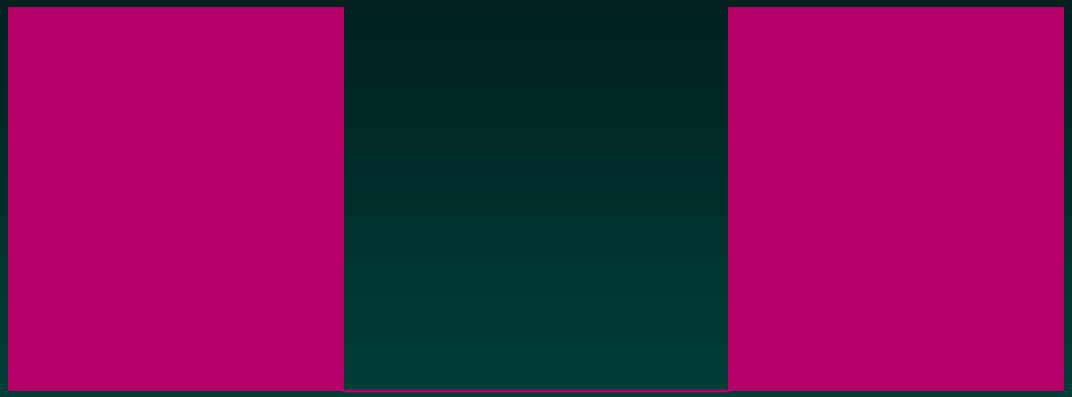
What is Variation?



A curve representing loss in quality as a function of a measured value

What is Variation?

Traditional “Loss Function”



Spec limits define acceptable and unacceptable quality

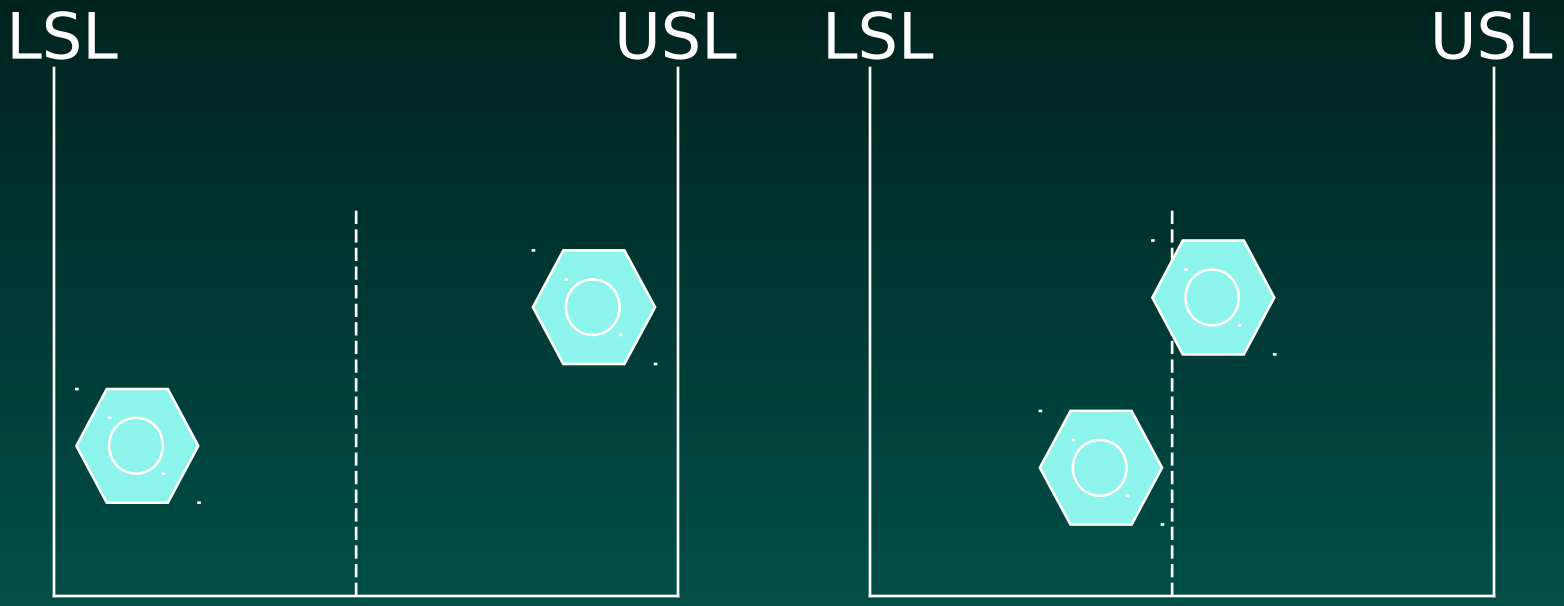
What is Variation?

Modern “Loss Function”

Target: Desired Value or Outcome

What is Variation?

How the Loss Function Affects Product



Both are within spec
Which is more desirable?

What is Variation?

Loss Function for Defects

What is Variation?

Less Variation

=

Higher Quality

Examining Variation

Definition

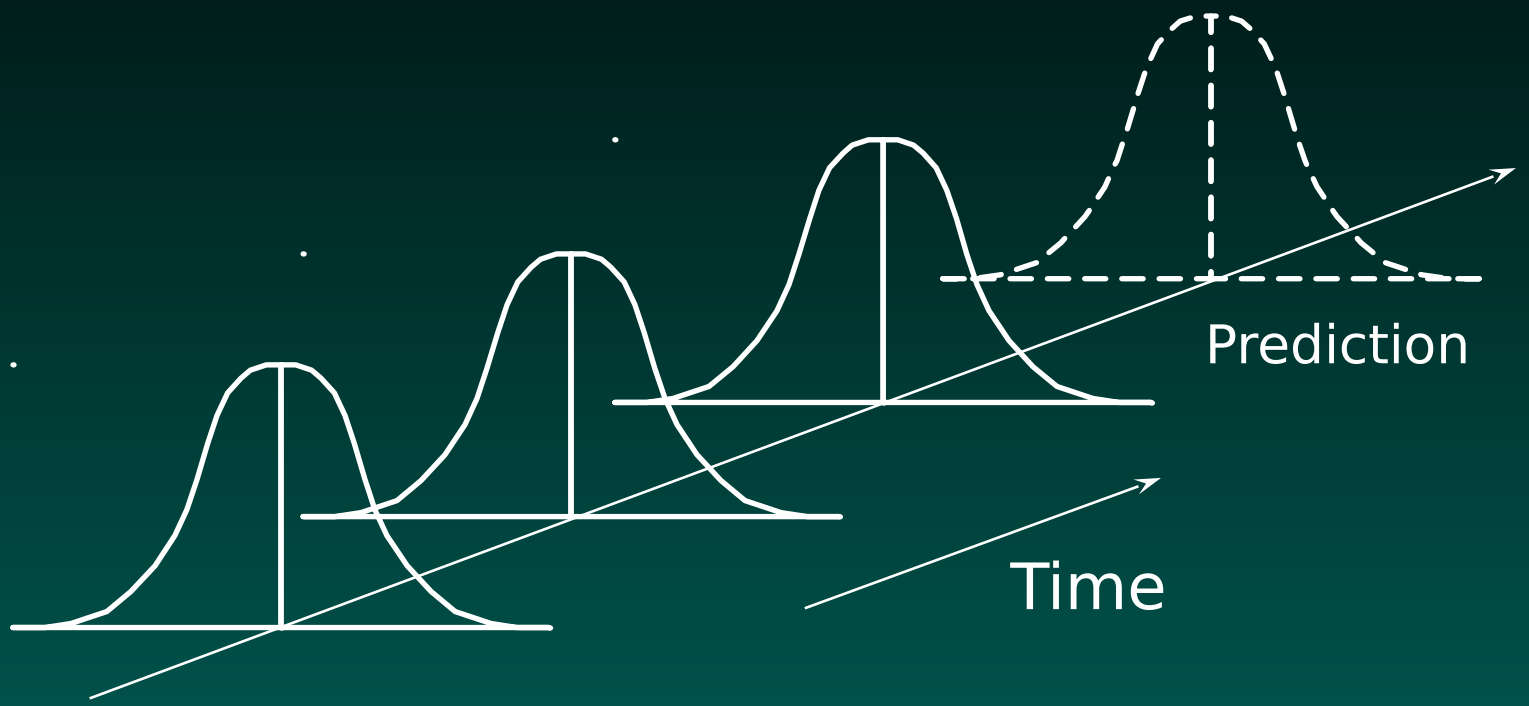
A **Stable Process** has the same normal distribution at all times.

A stable process is **In Control**

A stable process still has variation

Examining Variation

Stable Process



Normal distribution at all times

Examining Variation

Common Causes

The cause of variations in a stable process is called a **Common Cause**.

A common cause is a natural cause of variation in the system.

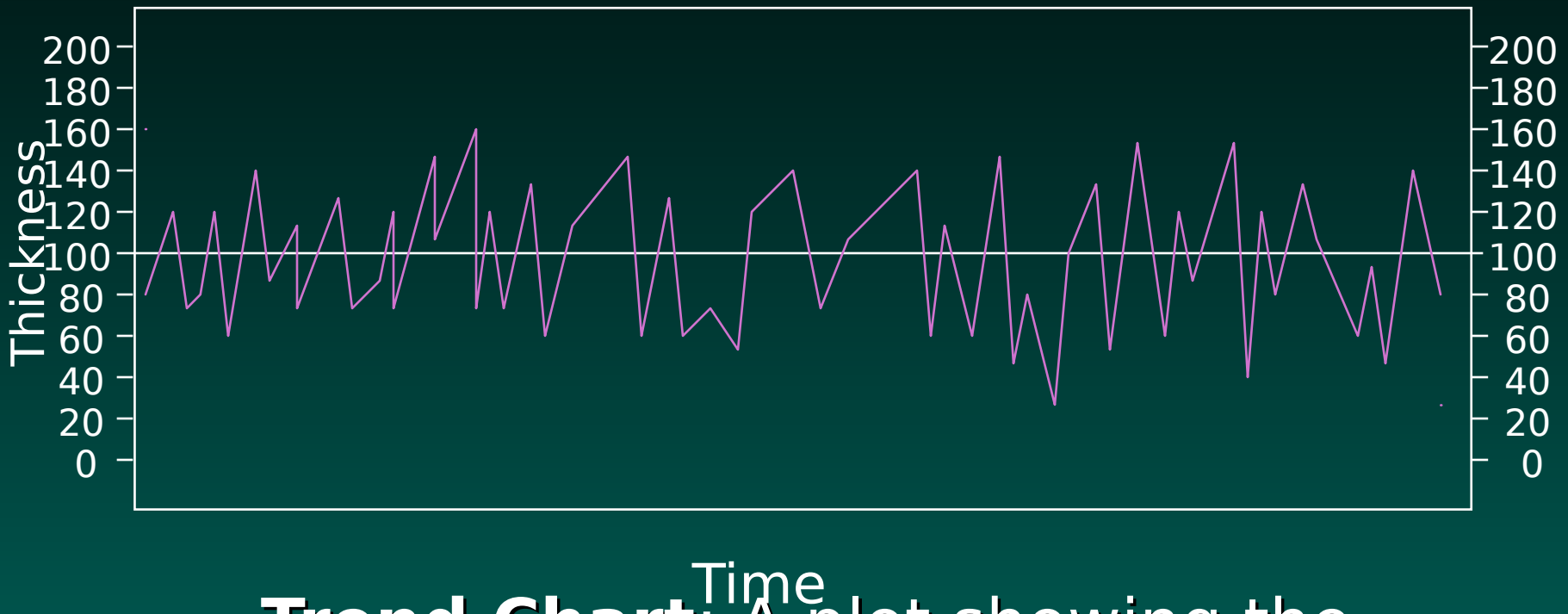
Examining Variation

Common Cause Examples

- ✓ Machine vibration
- ✓ Temperature fluctuations
- ✓ Slight variation in raw materials
- ✓ Human variation in setting control dials

Examining Variation

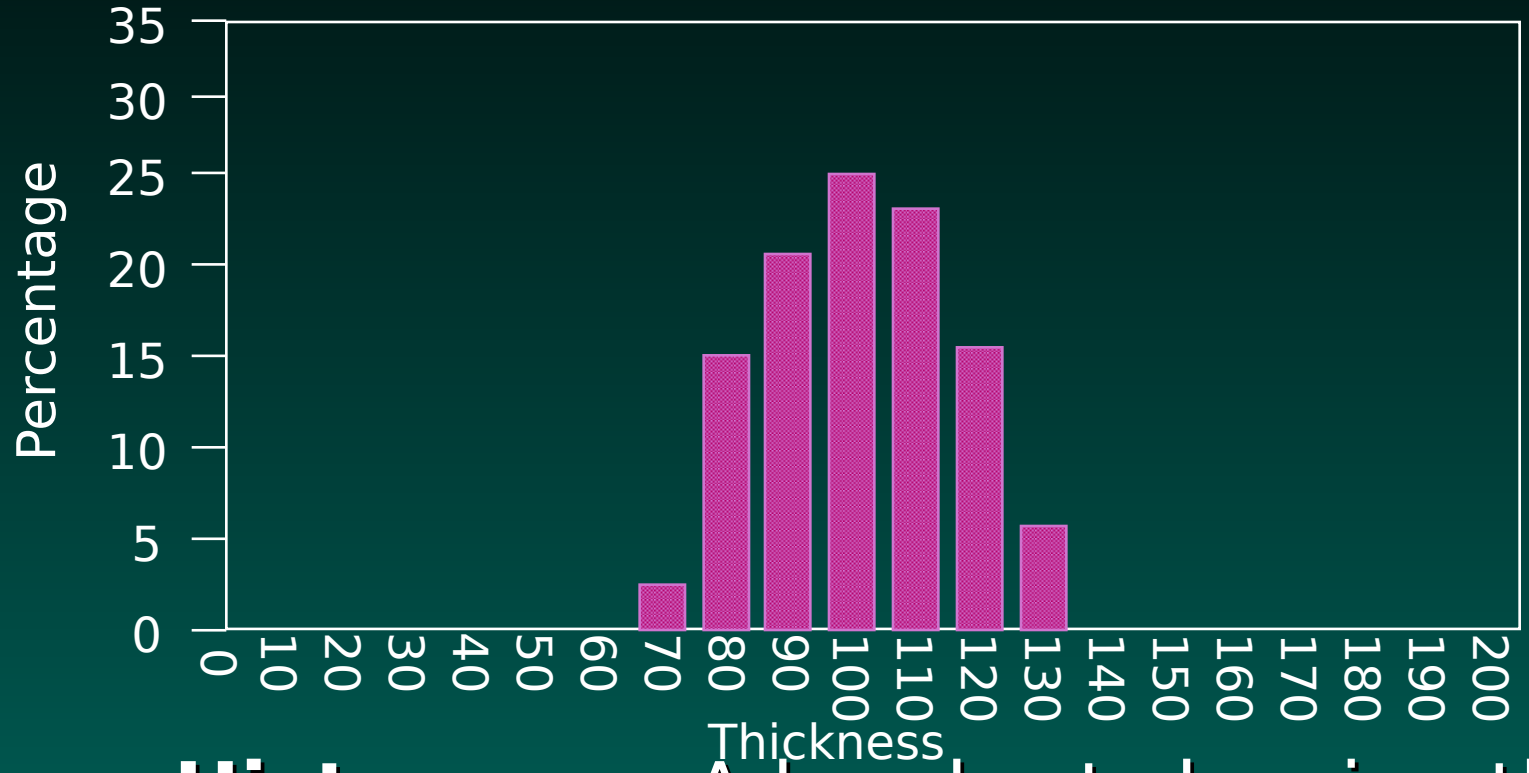
Tools for Examining Stability



Trend Chart: A plot showing the behavior of a process over time.

Examining Variation

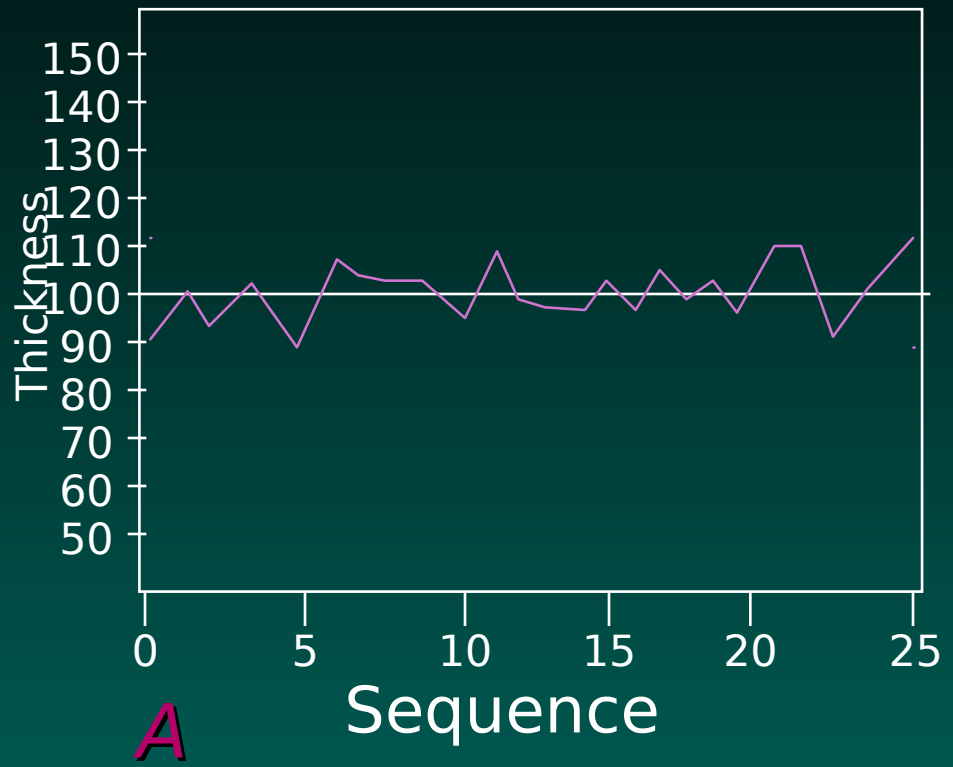
Tools for Examining Stability



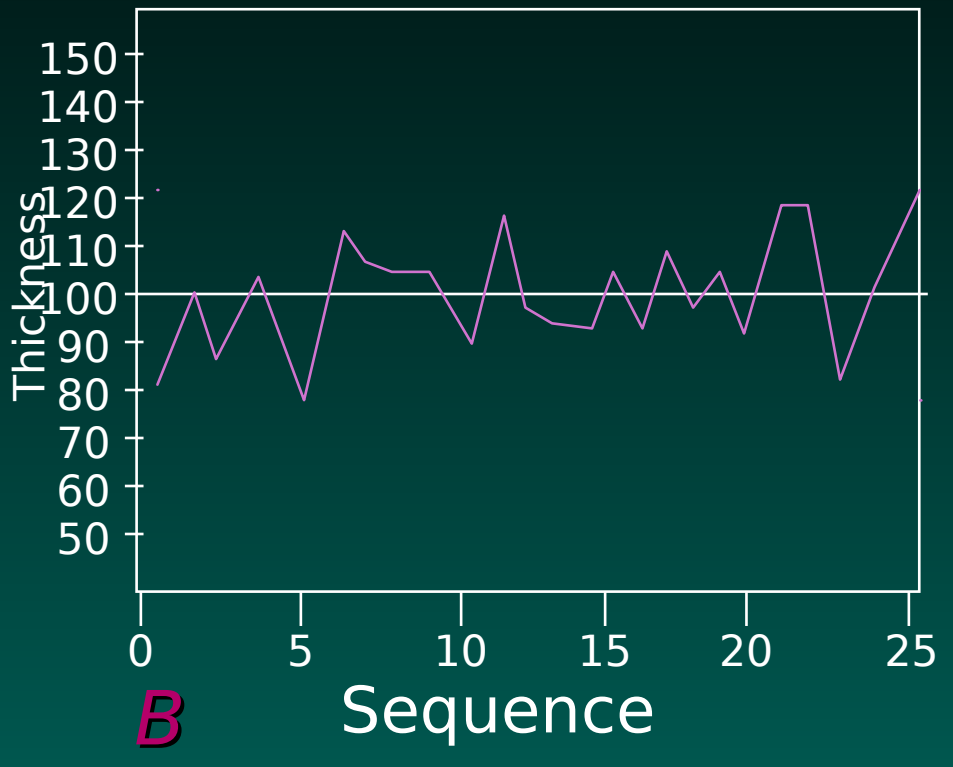
Histogram: A barchart showing the distribution of the process.

Examining Variation

Activity: Comparing stable processes



A

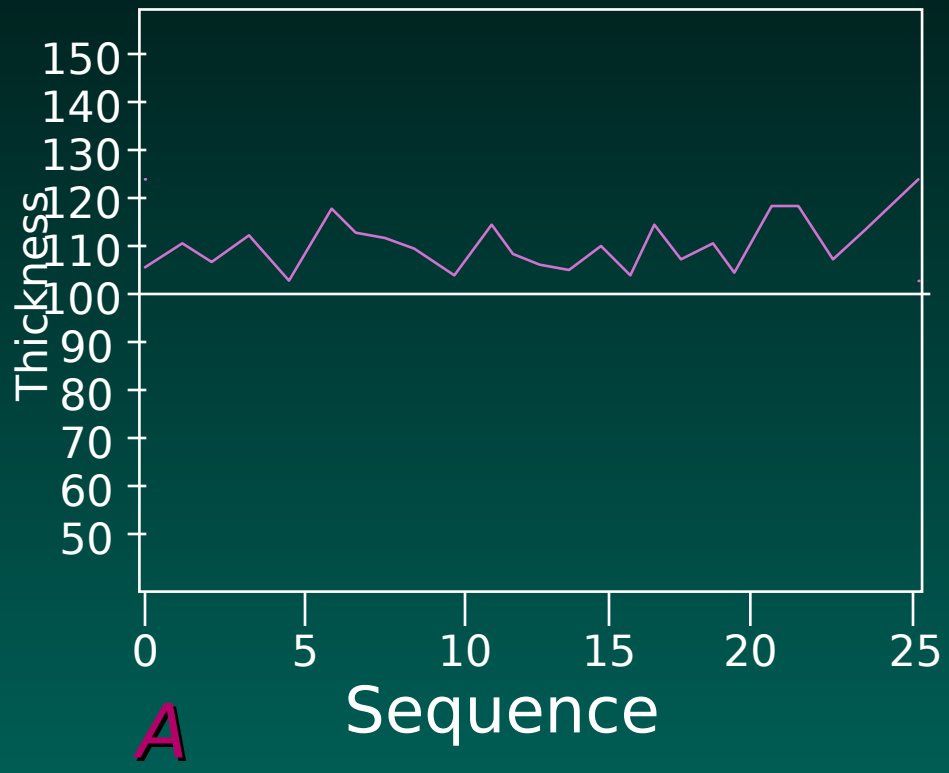


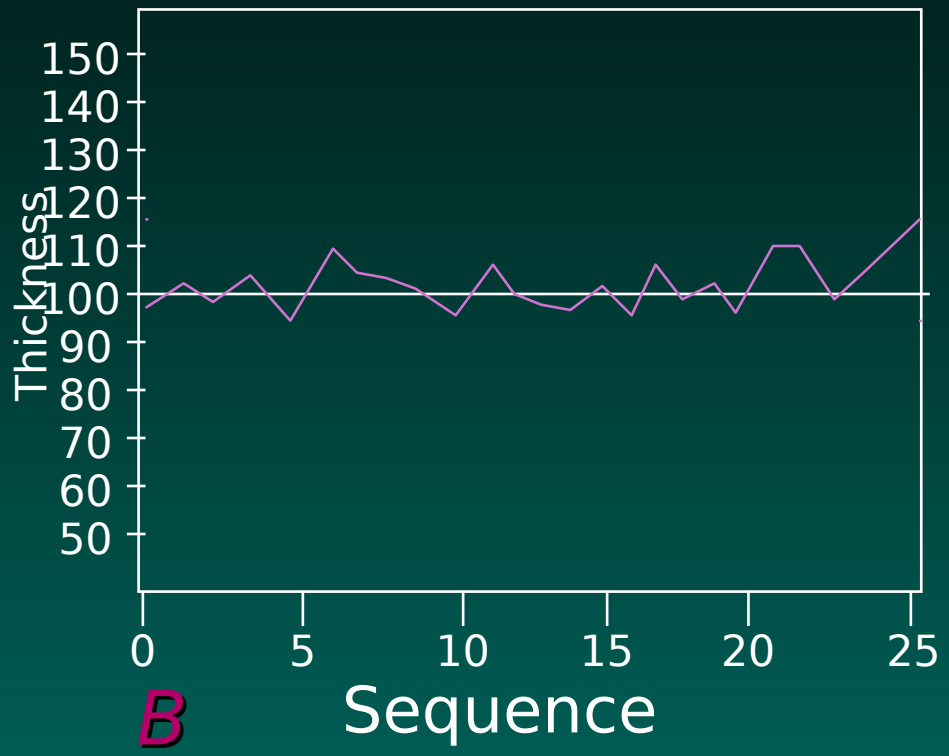
B

Which process has better quality?

Examining Variation

Activity: Comparing stable processes (cont'd)

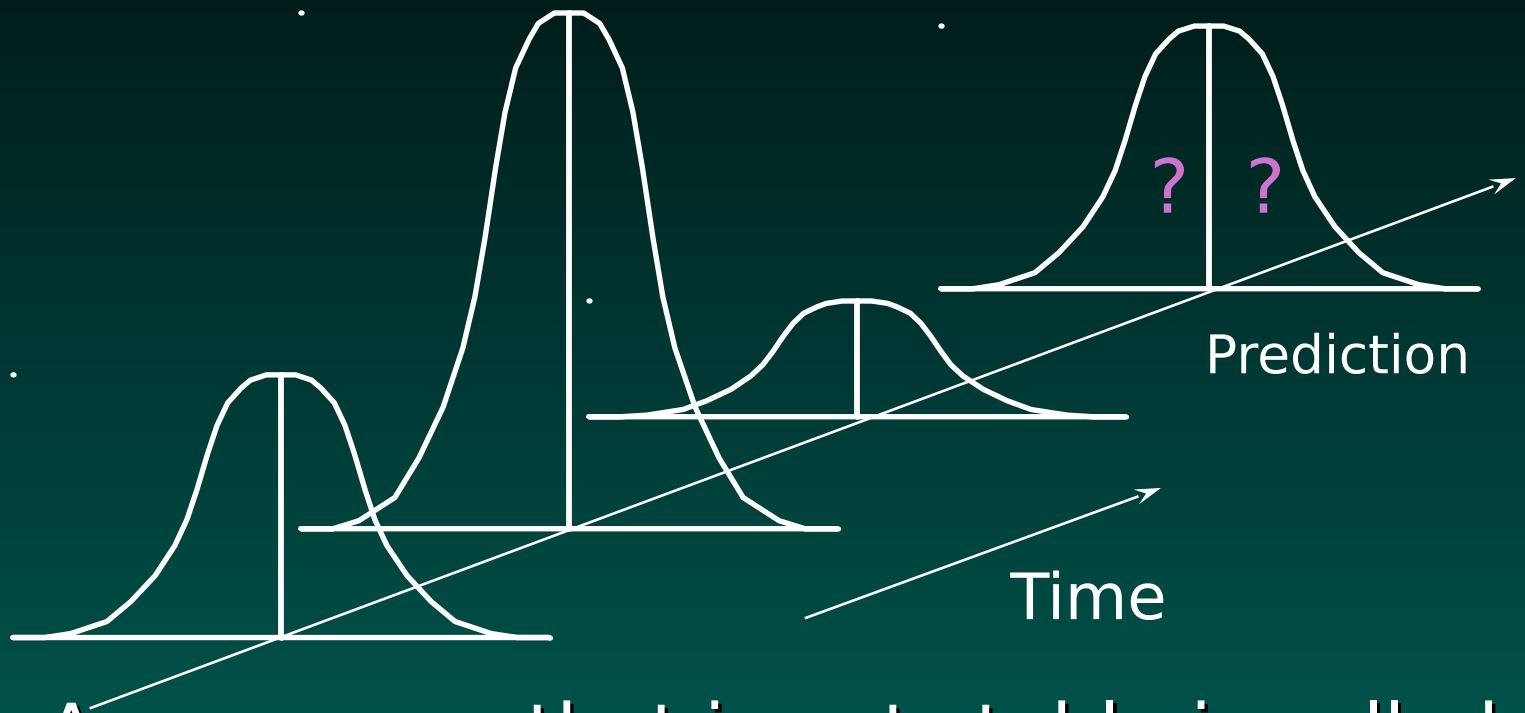




Which process has better quality?

Examining Variation

Unstable Process



Any process that is not stable is called an **unstable** or **out-of-control** process.

Examining Variation

Kinds of Instability: Excursions

Examining Variation

Kinds of Instability: Shifts

Examining Variation

Kinds of Instability: Drifts

Examining Variation

Kinds of Instability: Cycles

Examining Variation

Kinds of Instability: Chaos

Examining Variation

Special Causes

Anything that causes variations that are not part of the stable process is called a **special cause**, **assignable cause**, or **unnatural cause**.

Examining Variation

Examples of Special Causes

- ✓ Batch of defective raw material
- ✓ Faulty set-up
- ✓ Human error
- ✓ Incorrect recipe
- ✓ Blown gasket
- ✓ Earthquake

Reducing Variation

Improving a Stable Process

Two strategies for improving a stable process

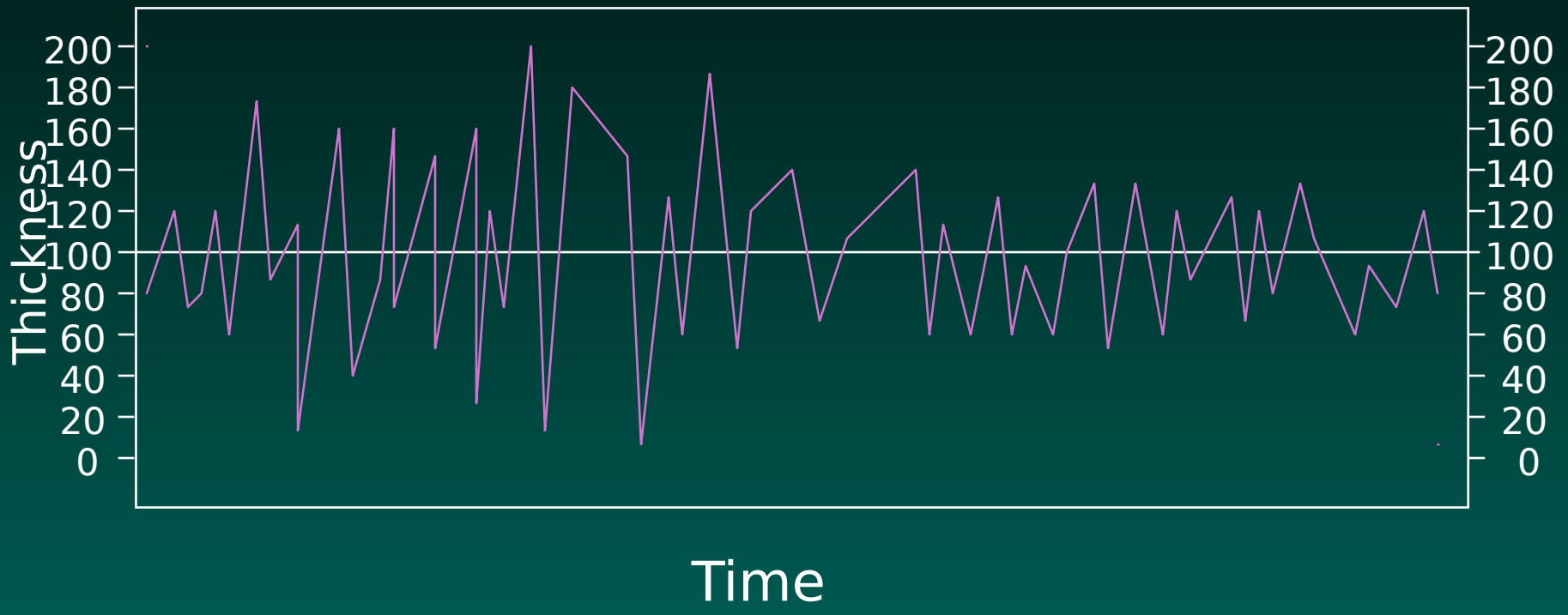
- ✓ Centering at Target
- ✓ Reducing Common Cause Variation

Reducing Variation

Centering at Target

Reducing Variation

Reducing Common Cause Variation



Reducing Variation

Reducing Variation in a Stable Process

Make Permanent Changes

Changes are based on the scientific approach

- ✓ Structured problem solving
- ✓ Planned experiments

Examples: new equipment, equipment upgrade, new procedure, new machine settings, better raw material

Reducing Variation

Reducing Variation in an Unstable Process

- ***Do not*** ignore special causes.
- ***Do*** quickly detect special cause variations.
- ***Do*** stop production until the process is fixed. (Reactive)
- ***Do*** identify and permanently eliminate special causes. (Preventive)

Reducing Variation

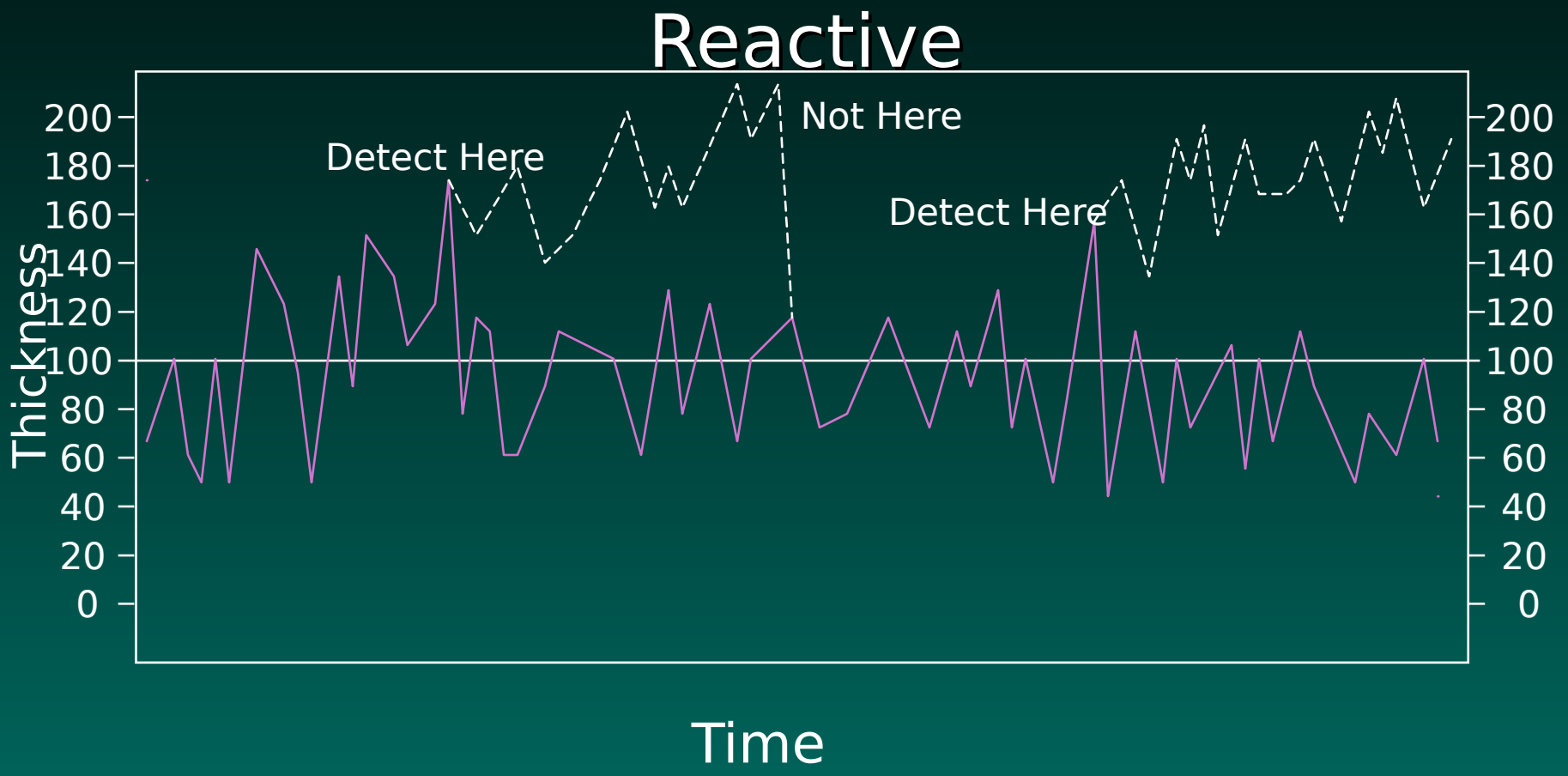
Improving an Unstable Process

Four Step Process

- ✓ Detect the special cause variation.
- ✓ Identify the special cause.
- ✓ Fix the process
  - Remove the special cause, or
  - Compensate for the special cause.
- ✓ Prevent the special cause from occurring again

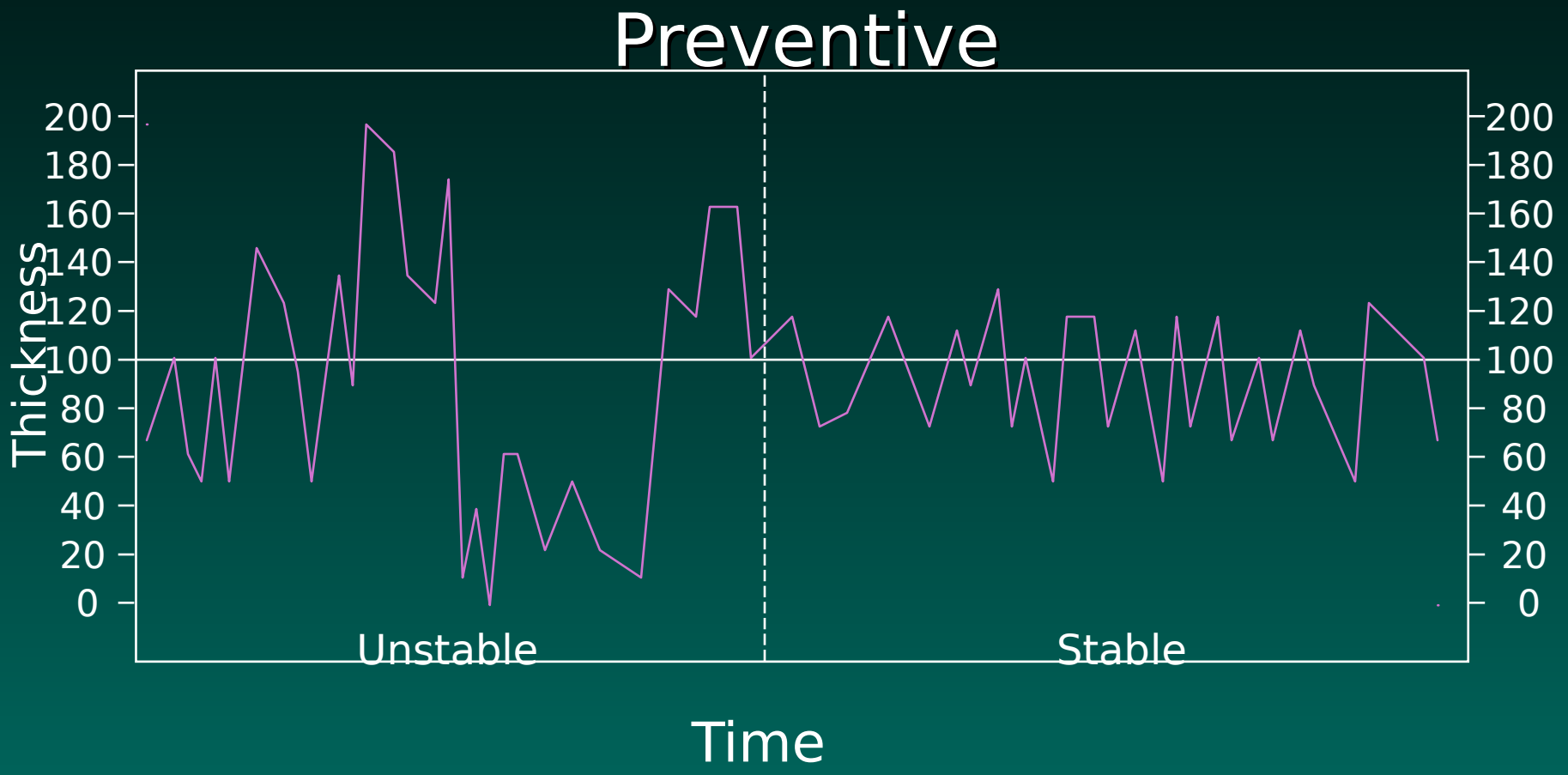
Reducing Variation

Improving an Unstable Process



Reducing Variation

Improving an Unstable Process

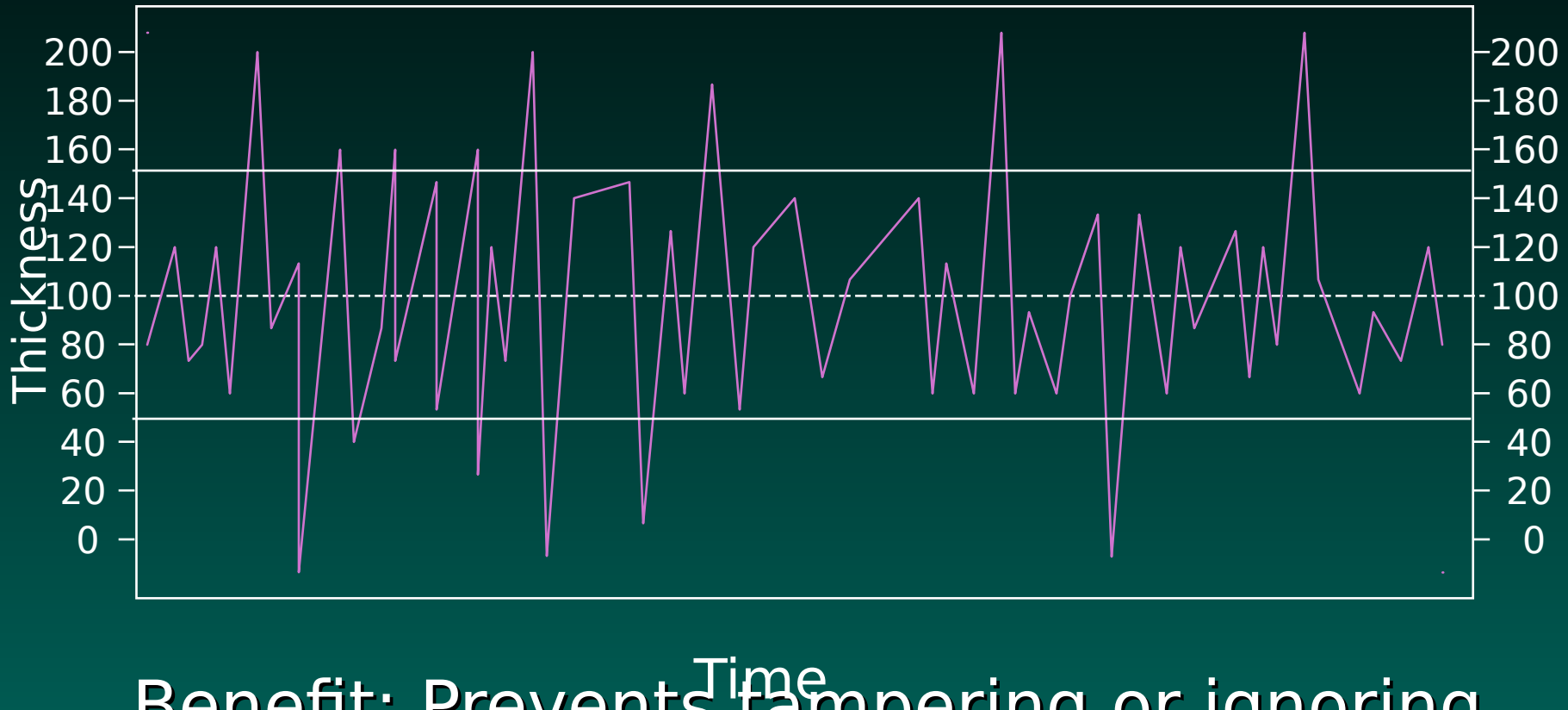


Detecting Variation

How can we decide if variation is the result of common or special cause?

Detecting Variation

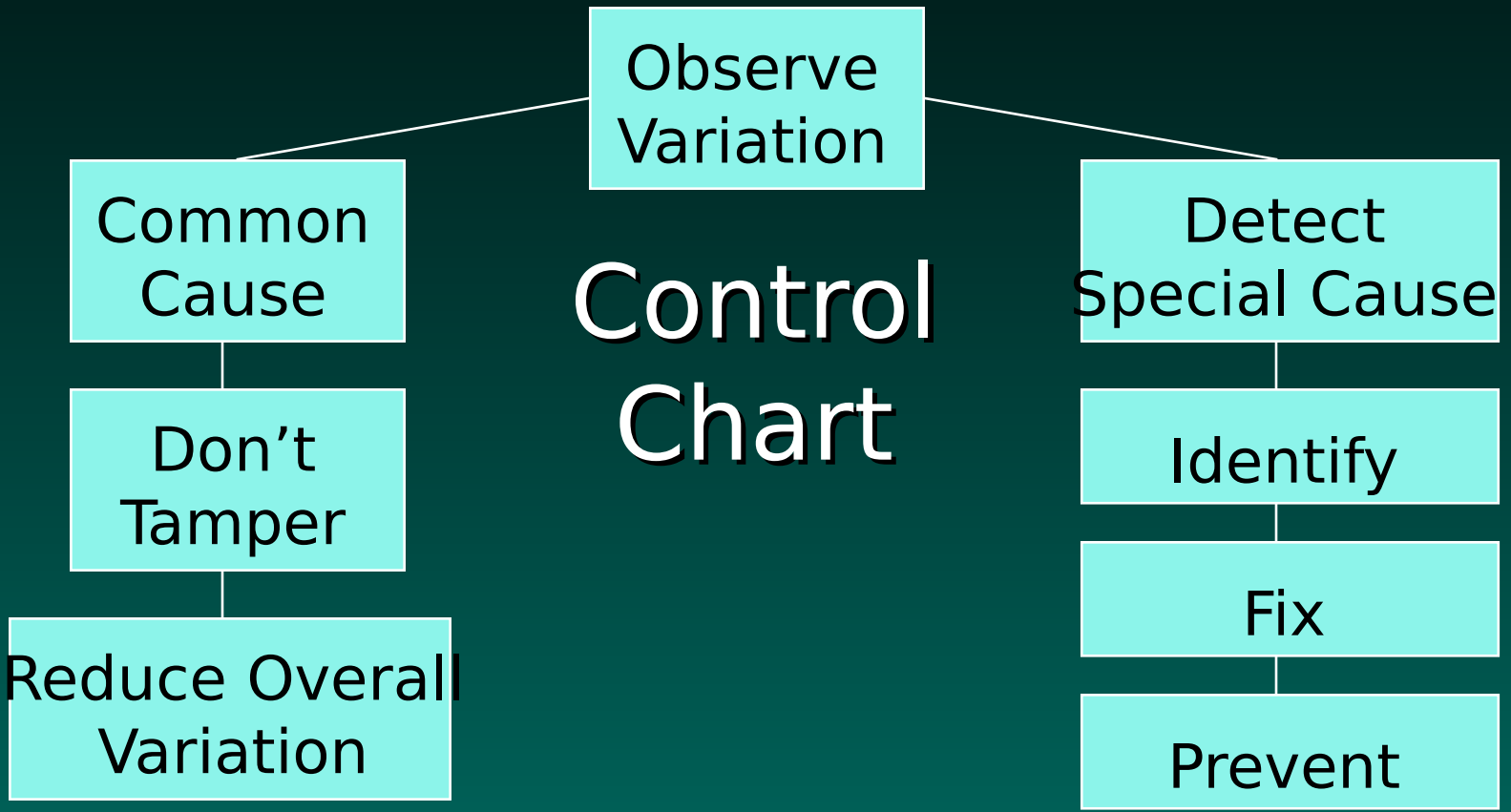
Tool: Control Chart



Benefit: Prevents tampering or ignoring

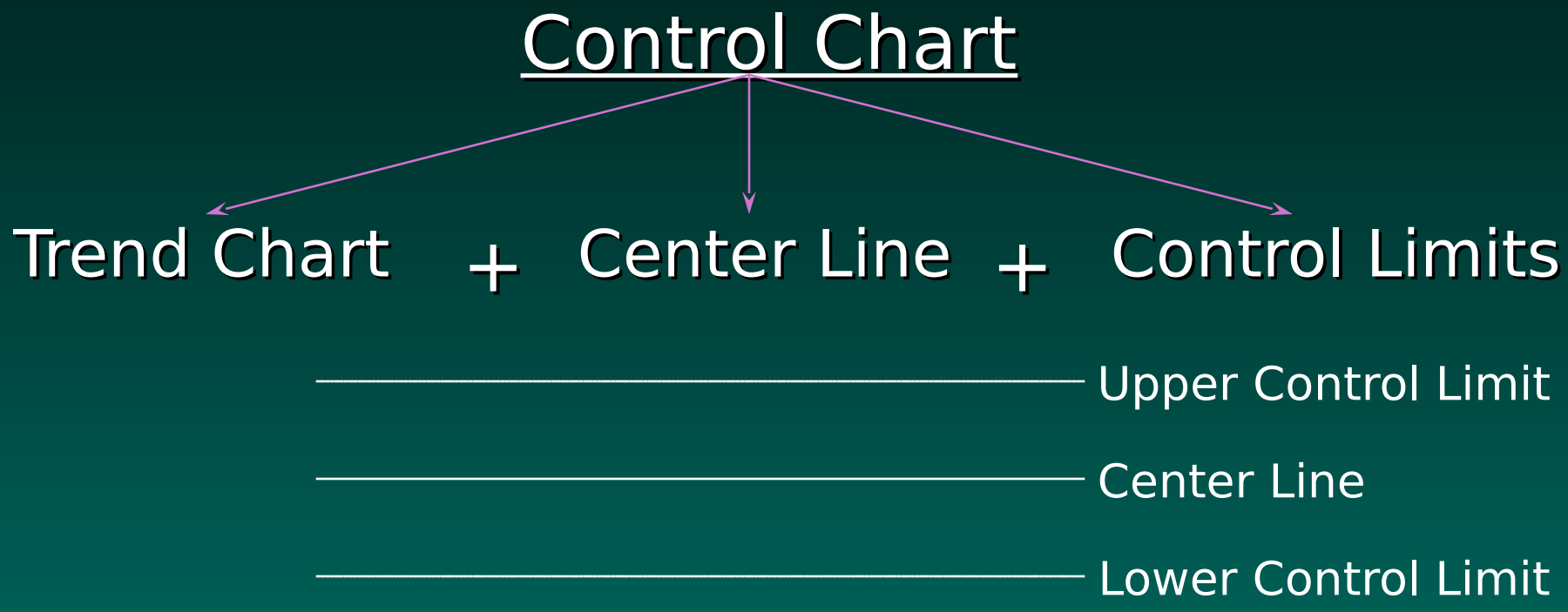
Detecting Variation

Control Chart for Detecting Variation



Detecting Variation

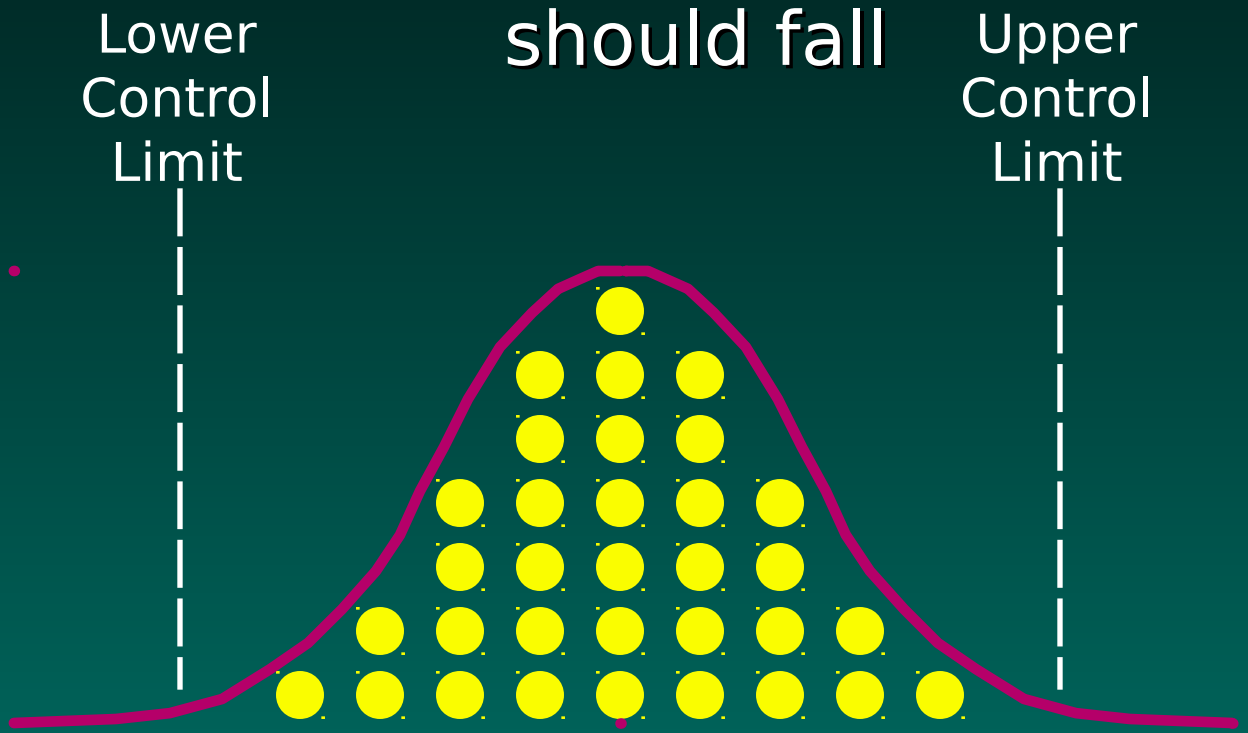
Control Chart for Detecting Variation



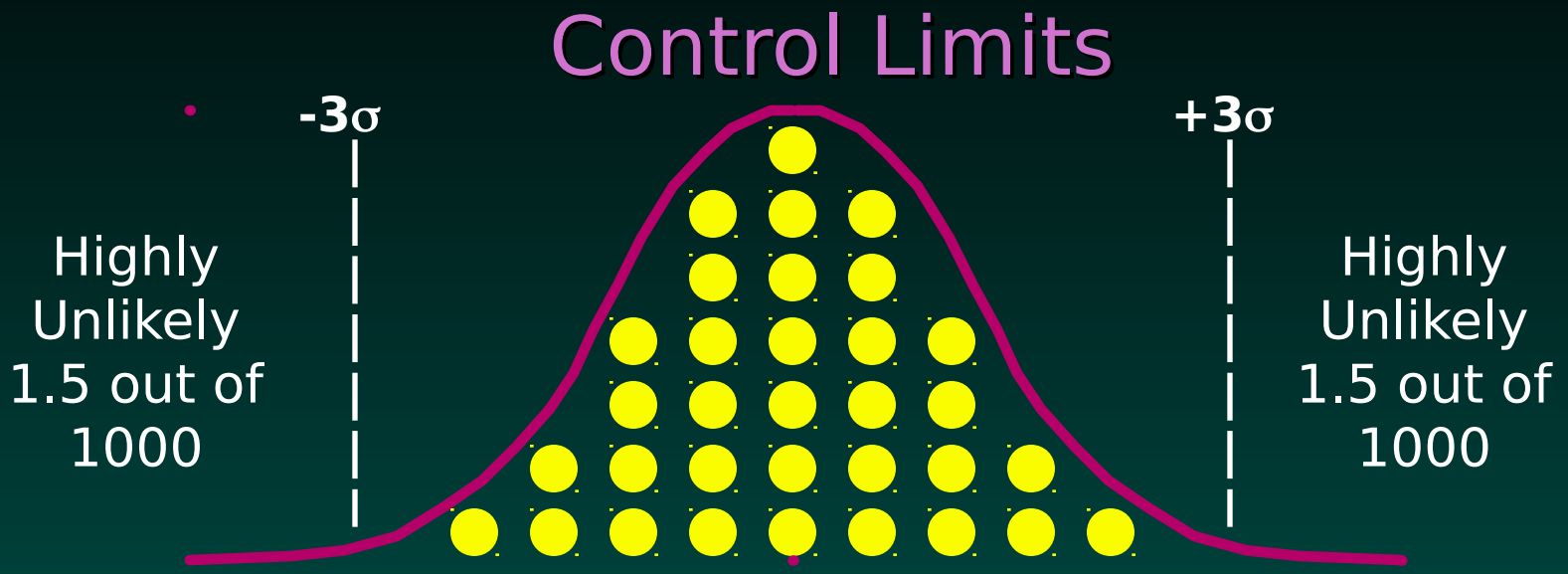
Detecting Variation

Control Limits

Control limits tell us where the measurements in a stable process should fall



Detecting Variation



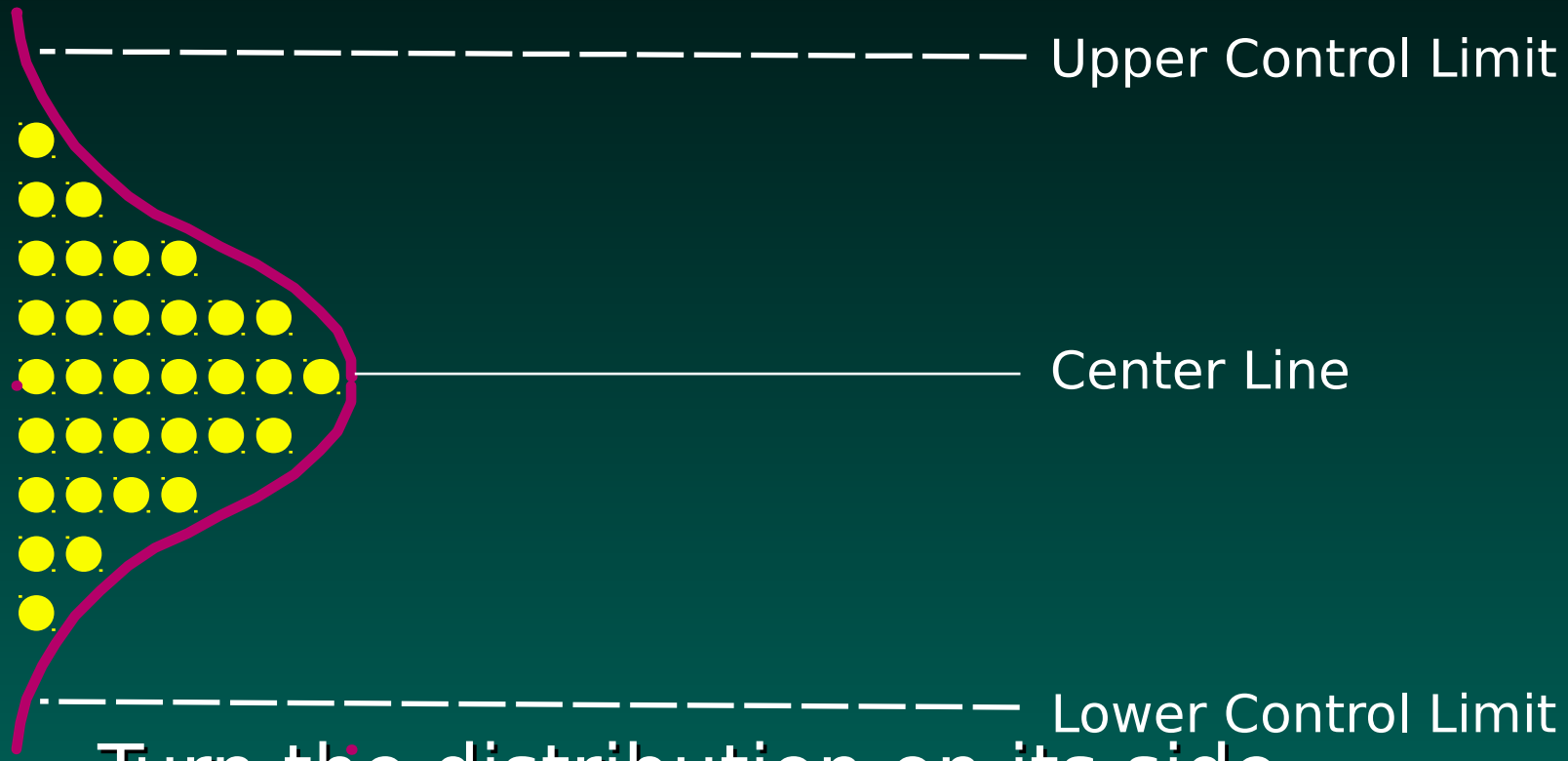
Calculated statistically, based on:

- Historical Data
- Characteristics of the stable process

Also called 6 sigma limits

Detecting Variation

Creating a Control Chart



Turn the distribution on its side

Detecting Variation

Can we use spec limits as control limits?

Can we compute control limits for an unstable process?

Detecting Variation

Creating a Control Chart

What is the Center Line?

Process mean, based on historical data

or

Process Target

Detecting Variation

Creating a Control Chart

Selecting the Center Line

Measurements: The center line should be the target, unless we are unable or unwilling to control the process to target.

Defects: Since the target is zero defects, the center line is the process mean.

Detecting Variation

Control Limits vs. Spec Limits

Control Limits

- Based on performance of the *process*.
- Tell us when to take action on the *process*.

Spec Limits

- Based on performance of the *product*.
- Tell us when to disposition the *product*.

Detecting Variation

Control Limits vs. Spec Limits

Focus On

Control Limits

Improve Process Quality

Improve Product Quality

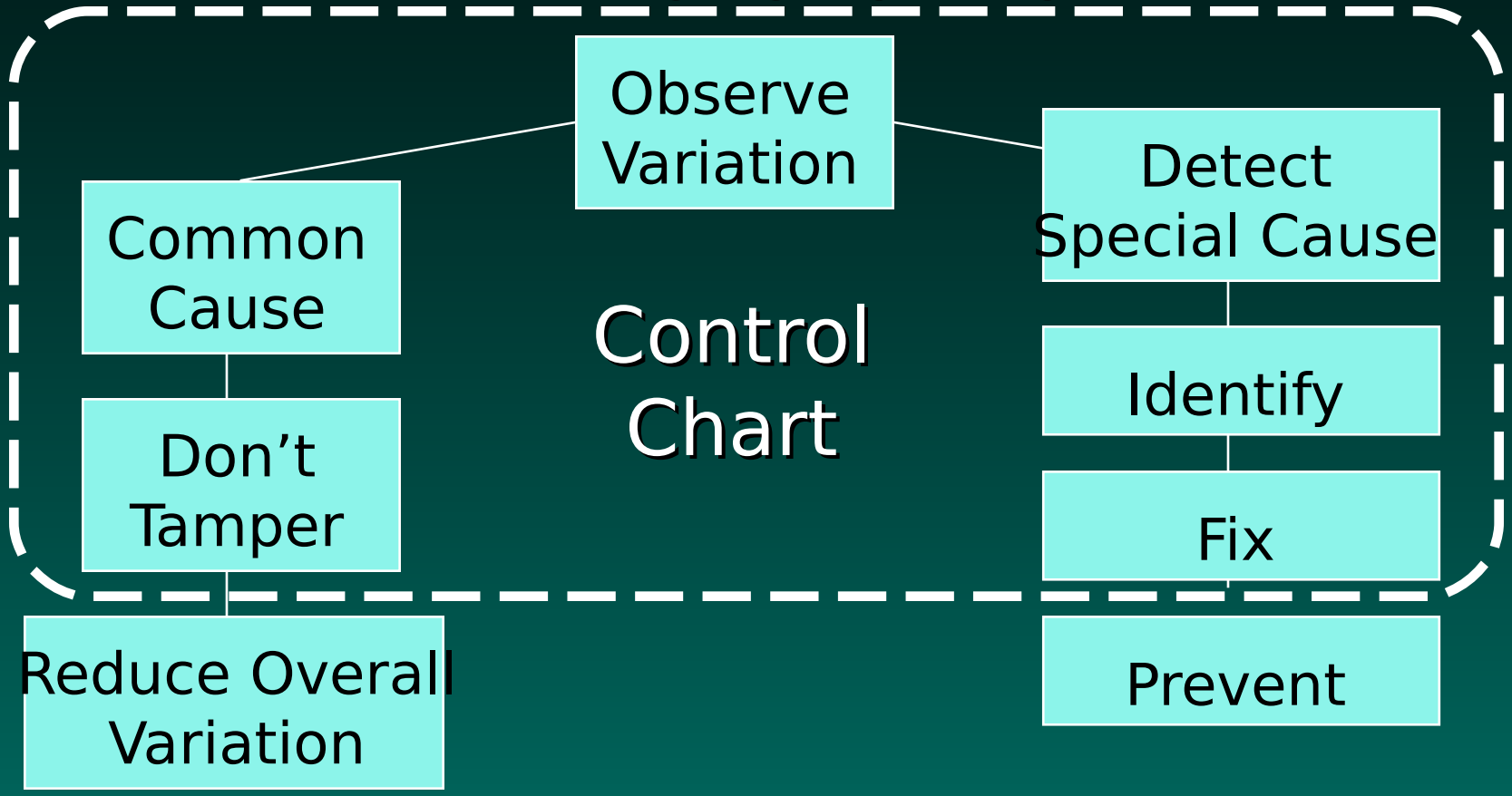
Detecting Variation

Uses of a Control Chart

- On-Line: Assess the present stability of a process, as part of a *process control system* (PCS)
- Off-Line: Assess the historical stability of a process

What is a PCS?

A PCS is a subset of the Reduction in Variation flow



What is a PCS?

Definition

A **process control system** is an on-line, real-time system for identifying and responding to process/equipment problems

What is a PCS?

Elements of a Process Control System

- ✓ Measurements
- ✓ Calculations
- ✓ Control Chart
- ✓ PCS Rules
- ✓ Response Flow

Elements of a PCS

PCS Rules

Set of rules applied to the data plotted on the control chart to determine if the process is stable or unstable.

Elements of a PCS

Response Flow

Sequence of actions followed to respond to an unstable process

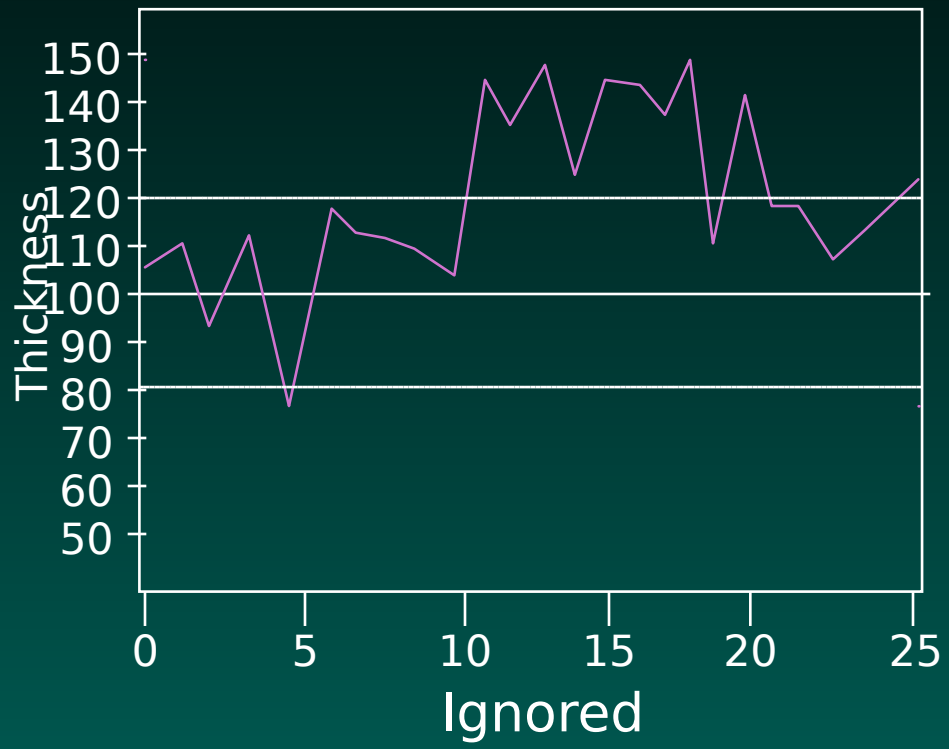
Elements of a PCS

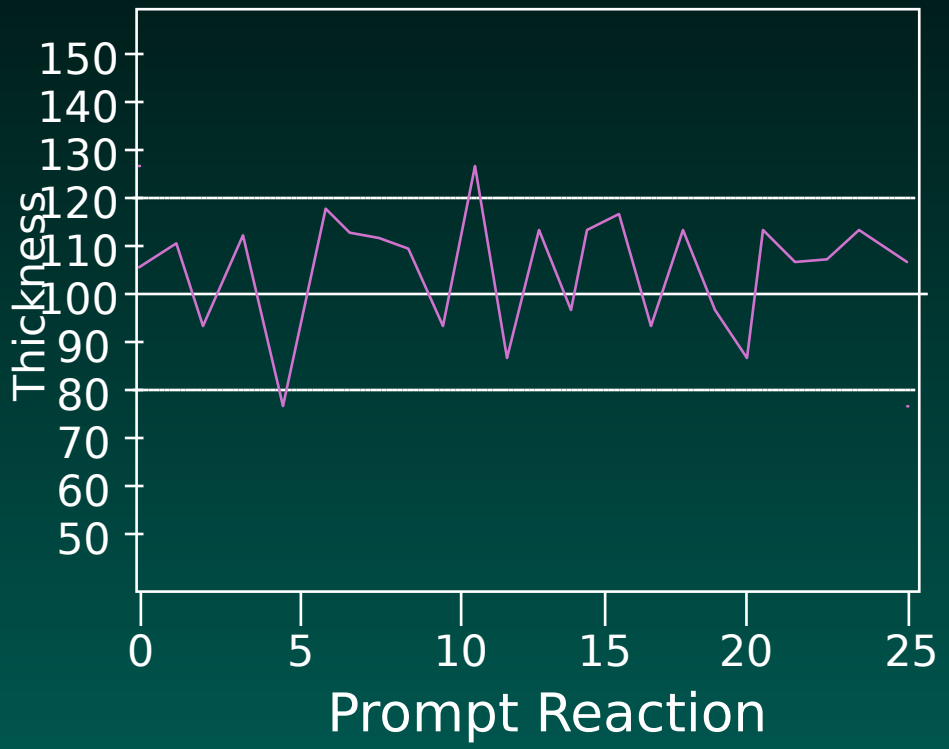
Example: Wafer film thickness

- ✓ Measure: Thickness in μs
- ✓ Compute: mean thickness
- ✓ Plot: mean thickness
- ✓ Apply PCS rules
  - A single point falls beyond the 3σ limit
  - 2 of the last 3 points fall between 2σ and 3σ
  - 8 points in a row fall on the same side of the center line
- ✓ Response Flow: Check calculations, check settings, ...

Why Use a PCS?

Compare the Control Charts

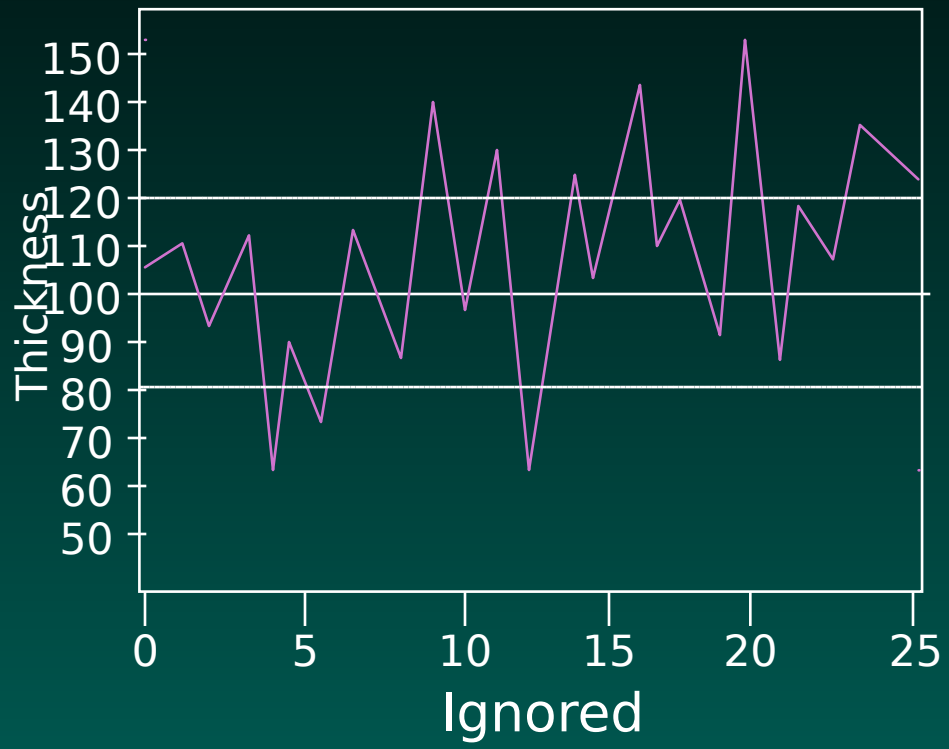


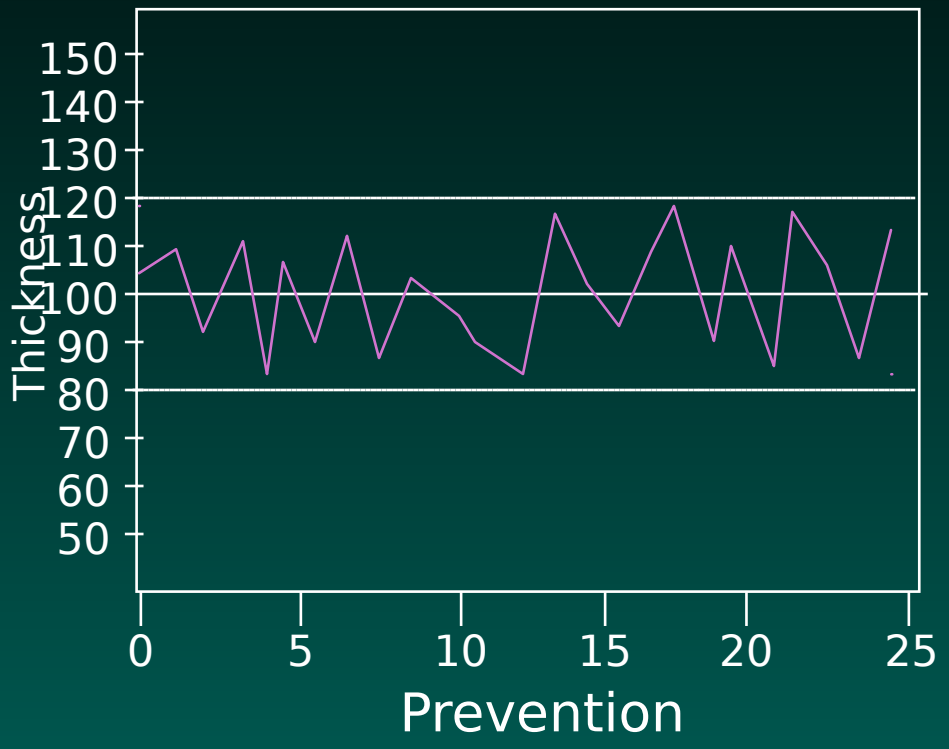


Which process is more desirable?

Why Use a PCS?

Compare the Control Charts





Which process is more desirable?

Why Use a PCS?

A PCS aids in reactive and preventive process improvement

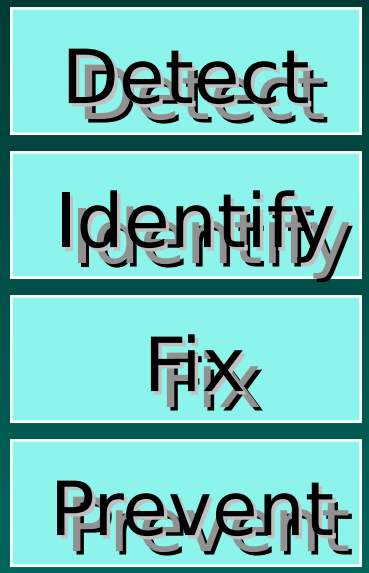
Measurements

Calculations

Control Chart

PCS Rules

Response Flow



Measurement Capability

Have you ever been bitten
by a measurement system?

black box

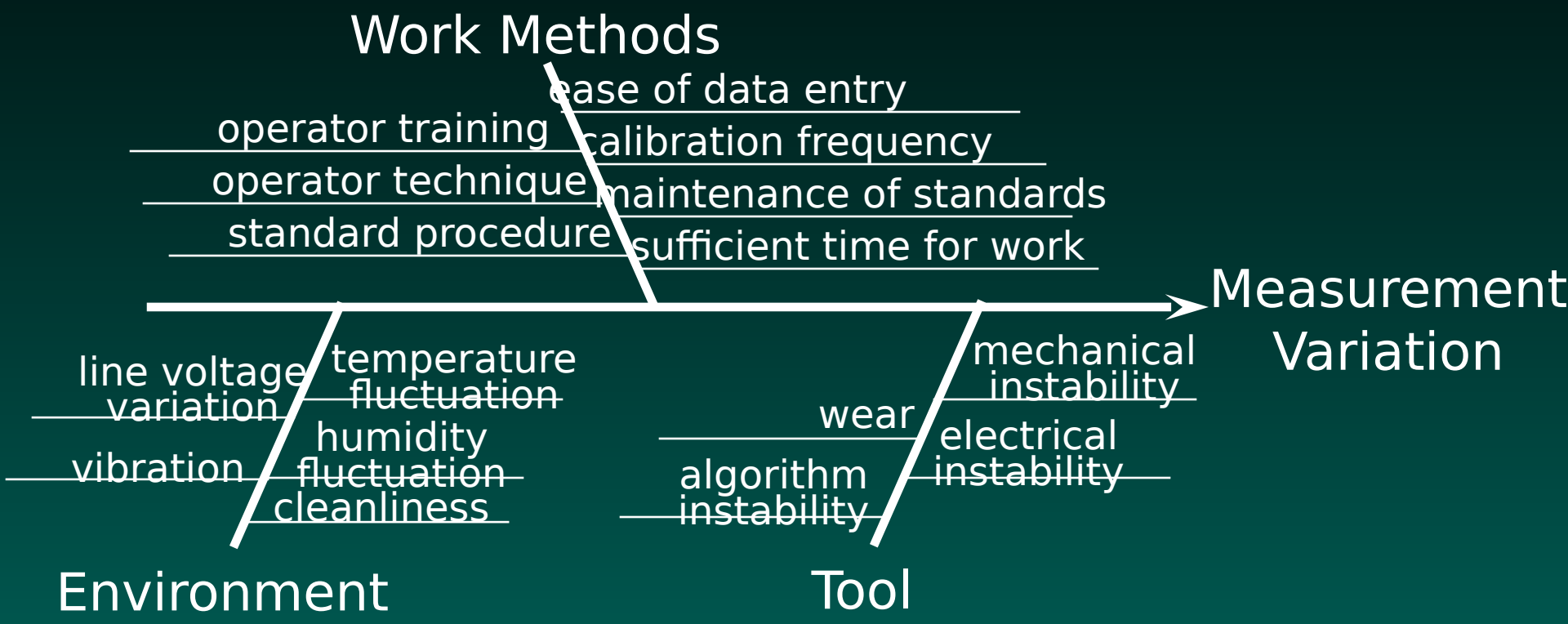
Measurement Capability

A Measurement Process

- Measurement tools themselves
  - hardware
  - software
- All the procedures for using the tools
  - which operators
  - set-up/handling procedures
  - off-line calculations and data entry
  - calibration frequency and technique

Measurement Capability

Why Do Measurements Vary?



NOTE: Not all of these will necessarily be significant sources of variation for every measurement system.

Measurement Capability

Assumptions We Often Make

- ✓ Metrology tools are perfectly accurate
- ✓ No day-to-day variation in performance
- ✓ No operator-to-operator variation

Measurement Capability

MCA Tells Us:

- ✓ How big is the measurement error?
- ✓ What are the sources of measurement error?
- ✓ Is the tool stable over time?
- ✓ Is the tool capable of making the measurements for this project?
- ✓ Is the tool capable of making the measurements for this process?
- ✓ What needs to be done to improve the measurement process?

Measurement Capability

Capability vs. Calibration

Calibration

Procedure to compare readings from a tool with a standard and then correct for any deviations.

Statistically: centering the mean of the distribution of readings on the “true value” (obtained from a standard).

Measurement Capability

Capability vs. Calibration (cont'd)

Capability

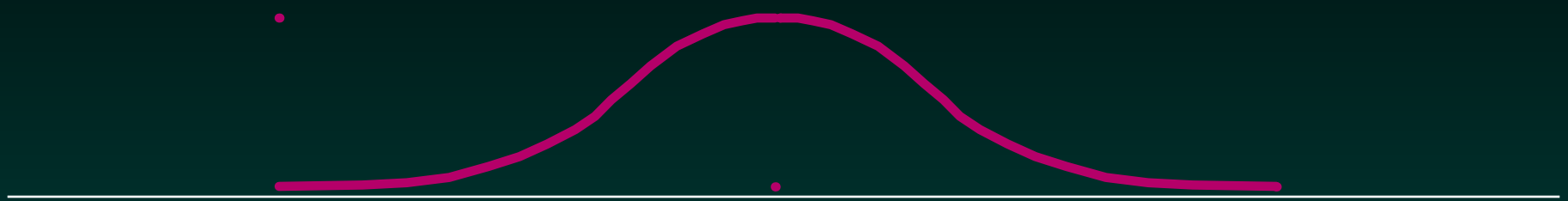
Procedure to identify and quantify sources of variation in readings and then eliminate them.

Statistically: fitting the model to the readings so that the components of variance can be estimated.

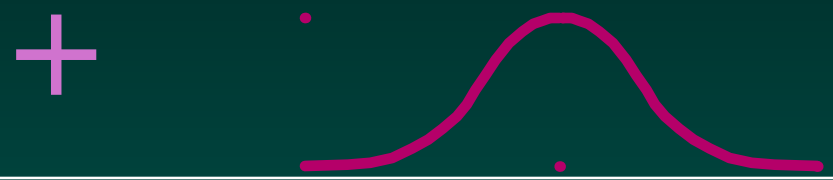
Both work together to keep measurement tool performing optimally.

Concepts and Vocabulary

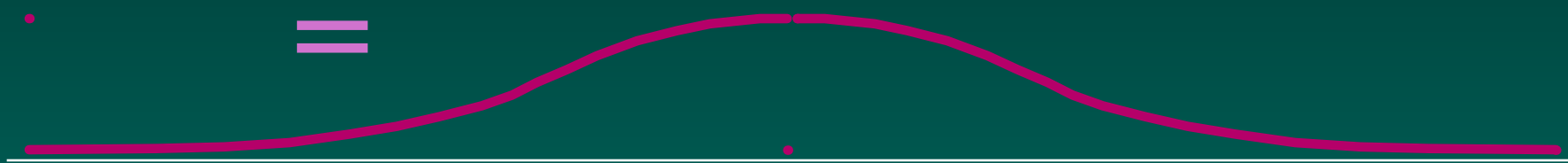
Sources Of Variation



Process Variation



Measurement Variation



Total Variation

Concepts and Vocabulary

Relationship Of These Distributions

Averages

$$\mu_{total} = \mu_{product} + \mu_{measurement\ error}$$

or, if the measurement tool is calibrated

$$\mu_{total} = \mu_{product}$$

Variabilities

$$\sigma^2_{total} = \sigma^2_{product} + \sigma^2_{measurement\ error}$$

Never Add Standard Deviations.

Note: These Relationships Are True Regardless Of The Distribution (Normal, Skewed, Bimodal, ...).

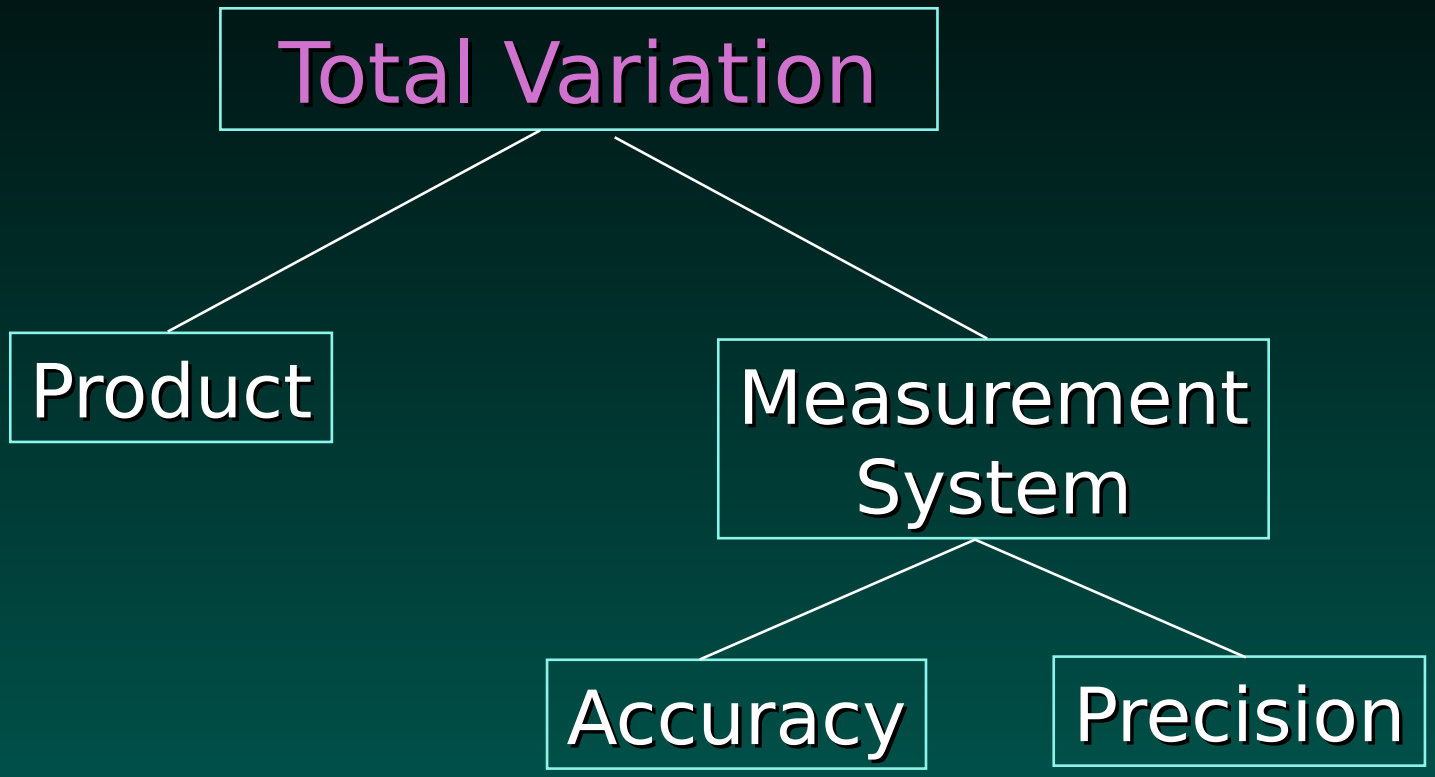
Concepts and Vocabulary

Activity

Suppose you have a process which has been operating for a significant period of time and has a σ of 10 units. Then a measurement capability study is done and the measurement error (σ_{ms}) of the metrology system is found to be 6 units.

- What is the true variability of the product?
- How could you confirm that?

Introduction



Concepts and Vocabulary

Accuracy

The degree to which a process mean is on target

Related Terms

True Value

Bias

Concepts and Vocabulary

Precision

The degree of variability in a process

Related Terms

Repeatability

Reproducibility

Concepts and Vocabulary

Bias

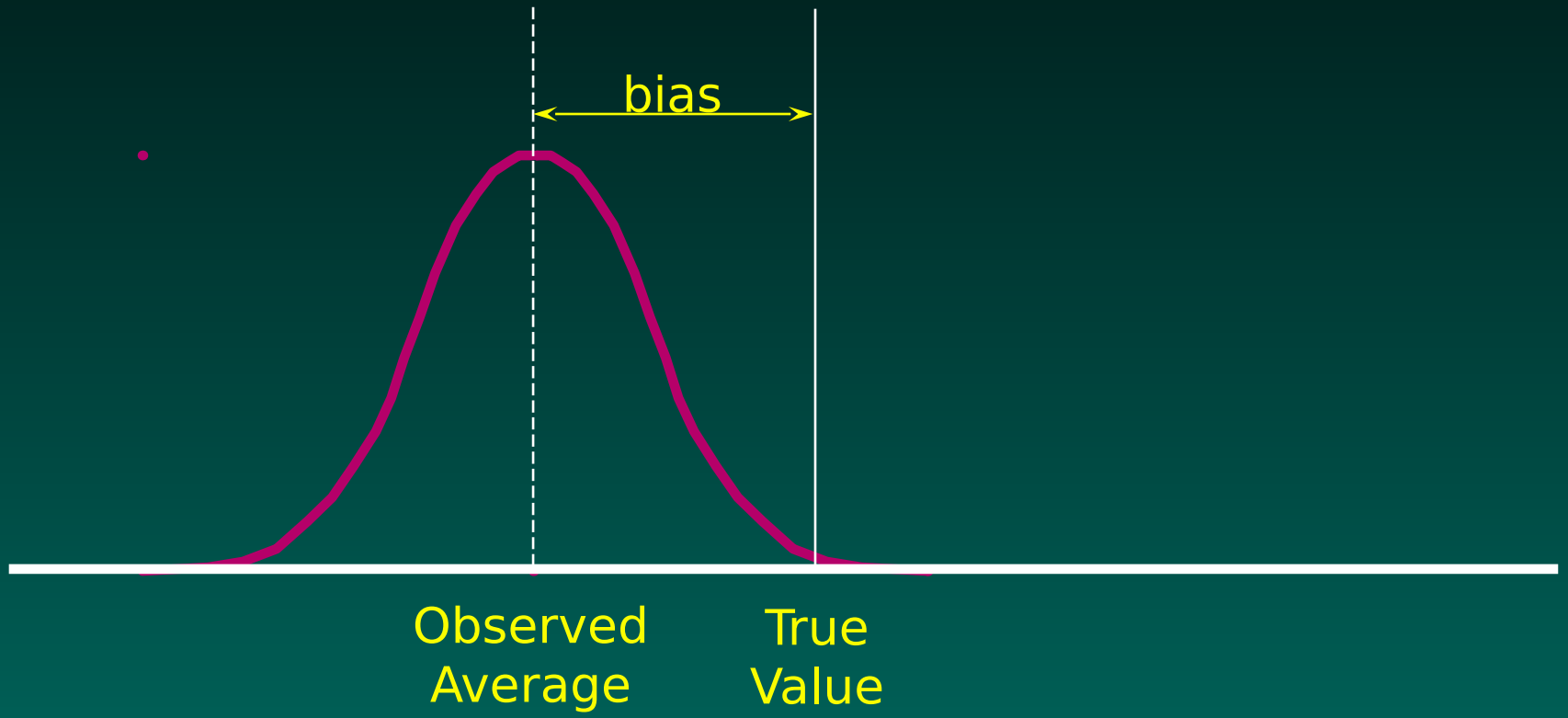
Distance between the average value of all the measurements and the **true value**. Can be positive or negative.

Bias = μ - True Value

- ✓ Measures the amount by which a tool is consistently off target from the truth.
- ✓ Bias is the numerical value we use to measure accuracy.
- ✓ Synonyms: systematic error, offset.

Concepts and Vocabulary

Bias



Concepts and Vocabulary

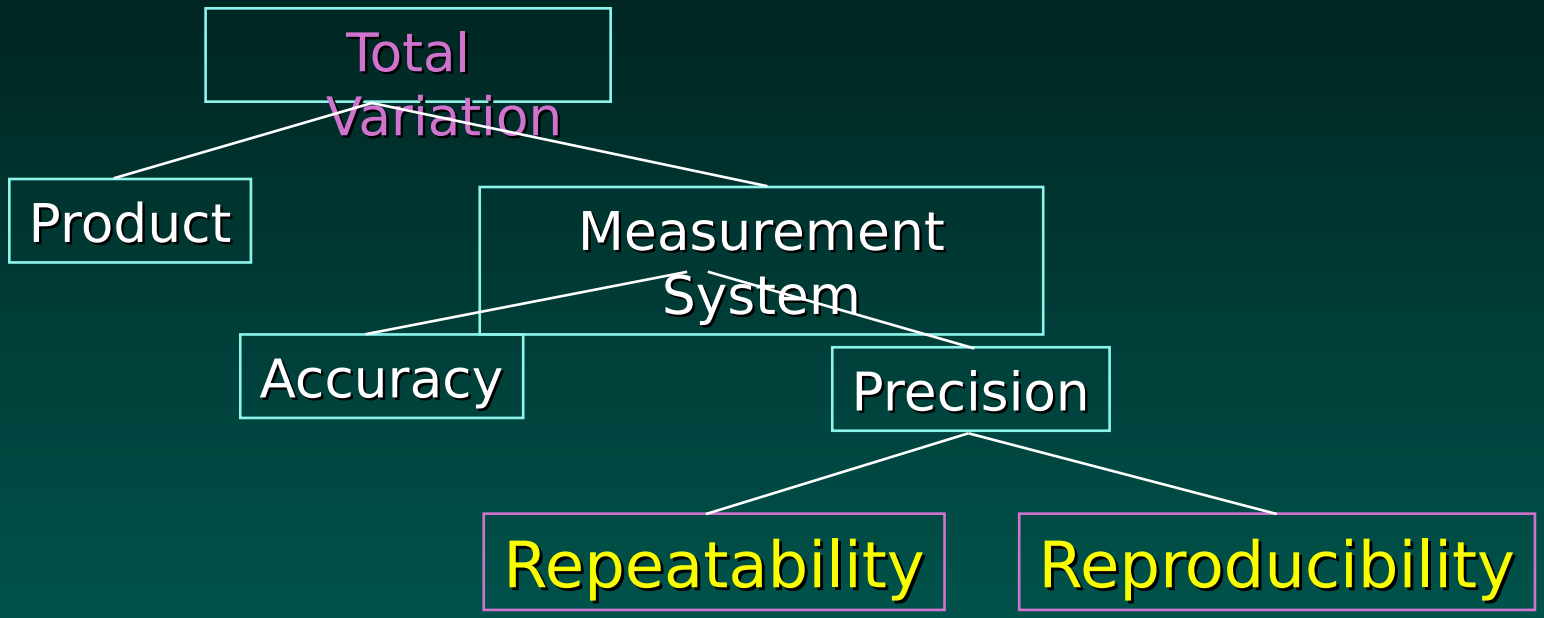
Precision Says Nothing About How Close The Measurements Are To The Truth.

Accuracy Says Nothing About How Close Measurements Are To Each Other.

Concepts and Vocabulary

Precision

Can be separated into repeatability and reproducibility



These characteristics have the relationship:

$$\sigma^2_{ms} = \sigma^2_{rpt} + \sigma^2_{rpd}$$

Concepts and Vocabulary

Repeatability

Variation that results when repeated measurements are made of the same parameter under absolutely identical conditions.

- ✓Same operator
- ✓Same set-up procedure
- ✓Same part
- ✓Same environmental conditions

Repeatability (σ^2_{rpt}) is usually much smaller (better) than the precision of the system.

Concepts and Vocabulary

Reproducibility

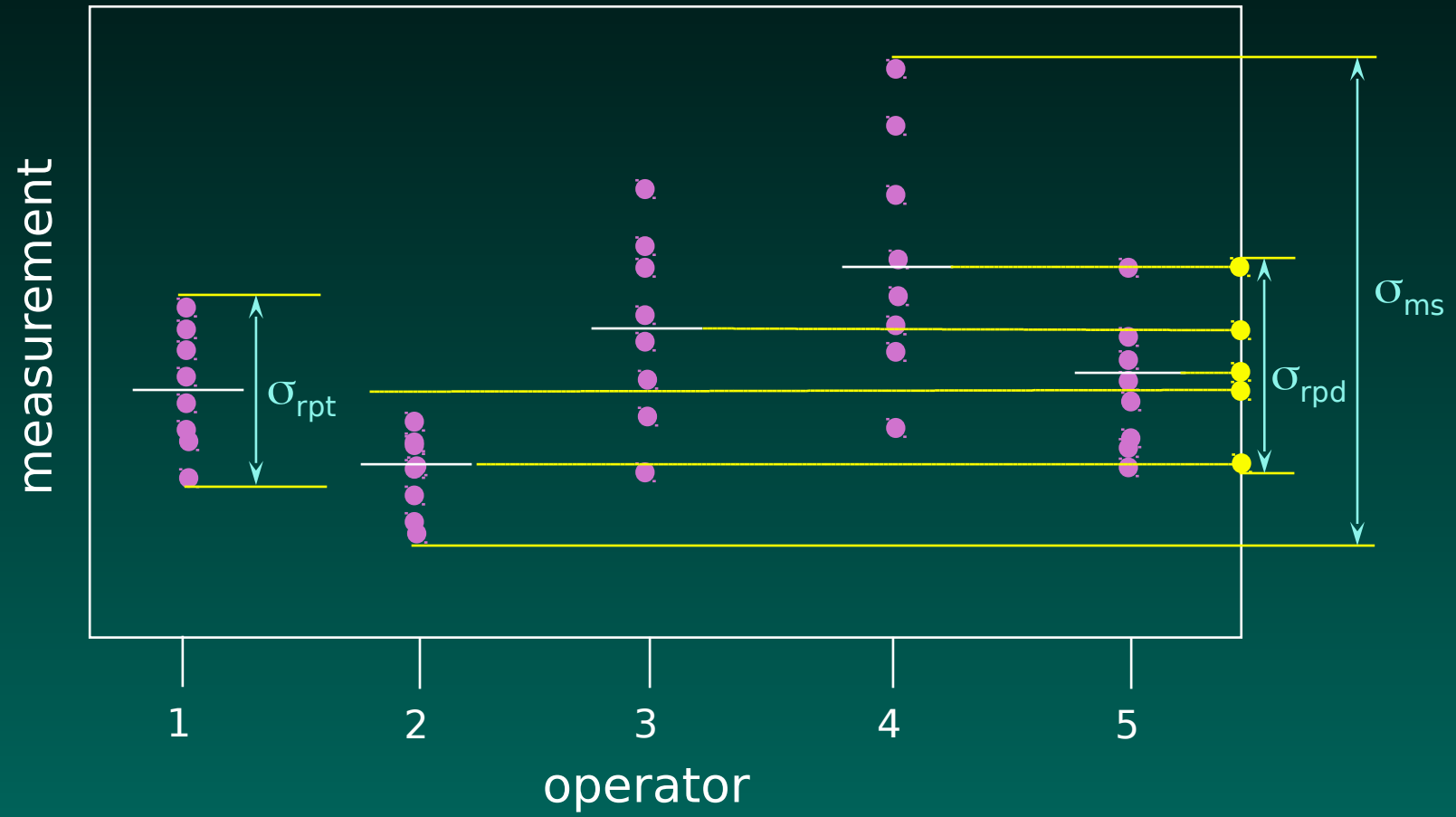
The variation that results when different conditions are used to make the measurement.

- ✓Different Operators
- ✓Different Set-Up Procedures
- ✓Different Measurement Tools
- ✓Different Environmental Conditions
- ✓Different Days

Reproducibility (σ_{rpd}), is approximately the standard deviation of the averages of measurements from different measurement conditions.

Concepts and Vocabulary

Repeatability vs. Reproducibility



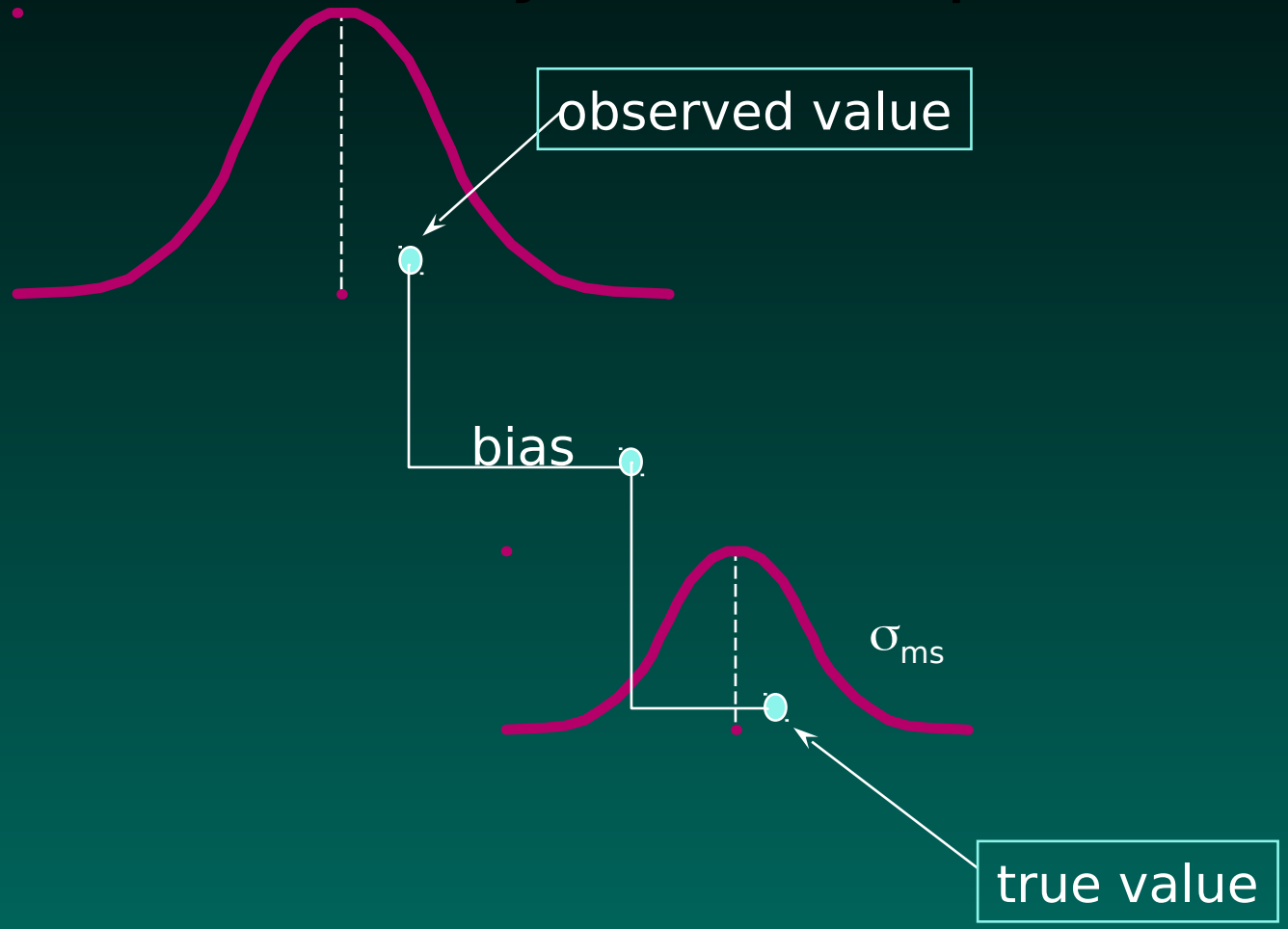
Concepts and Vocabulary

Suppose the results of your measurement capability study show that σ_{rpt} is 2.4 Units and σ_{rpd} is 1.1 Units.

What Is The Precision?

Concepts and Vocabulary

Summary of Concepts



Capability Indices

Now that we understand the impact that measurement has on variation, how can we determine its impact on the product and process?

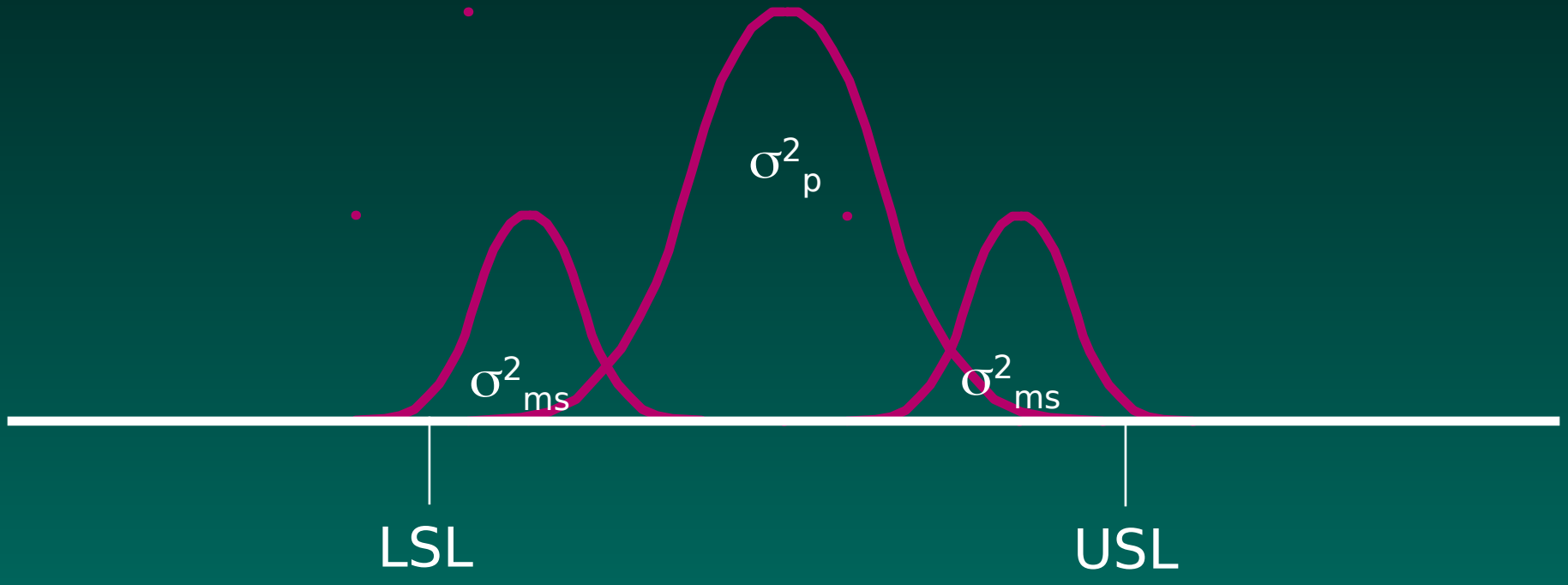
Two Approaches

- ✓ Compare measurement error to specs
- ✓ Compare measurement error to process variability

Capability Indices

Compare Measurement Error To Specs

"How much of the specs window is eaten up by measurement error"?



Capability Indices

Compare Measurement Error to Specs

P/T = Precision/Tolerance Ratio

$= 6 * \sigma_{ms} / (USL - LSL)$

- ✓ Tolerance = Upper Spec Limit - Lower Spec Limit
- ✓ You Want P/T To Be Small.
- ✓ The position of the measurement distribution relative to the product specs does not matter!

Capability Indices

Compare Measurement Error To Specs

- P/T is designed to measure how much of the spec window is lost to measurement error.
- P/T uses only the standard deviation of the measurement error distribution.

Recall that $\sigma^2_{total} = \sigma^2_p + \sigma^2_{ms}$

Capability Indices

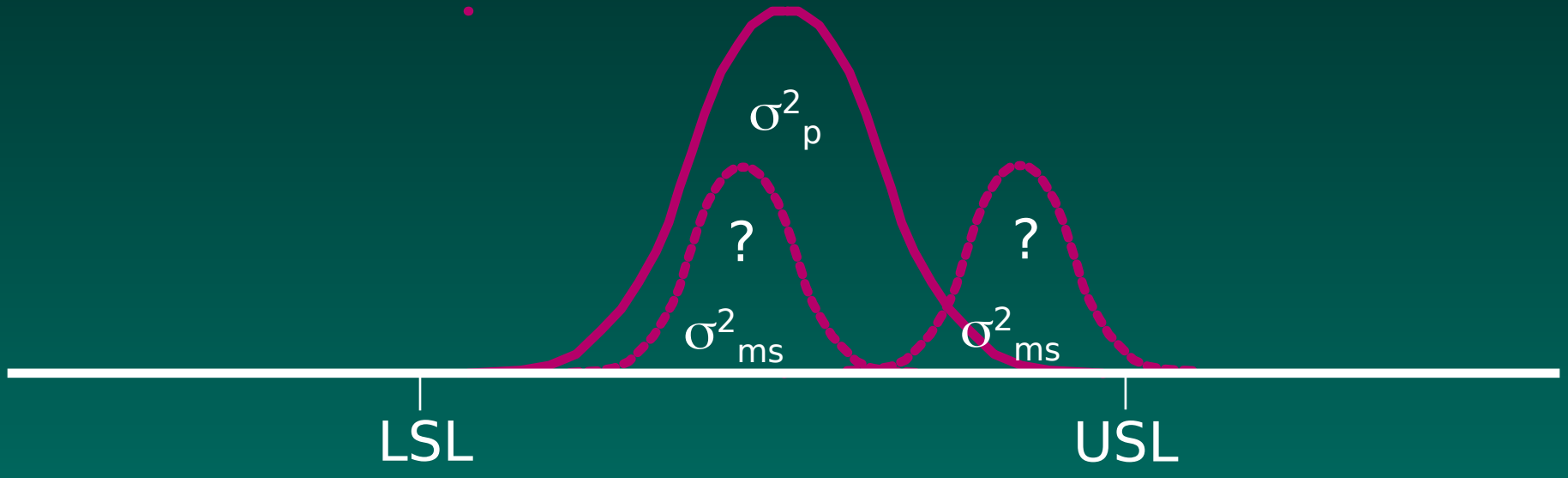
Interpretation of P/T

Large P/T Increases the Probability That We Will Misclassify Product As Defective When Really It Is Good, or Misclassify the Product As Good When It Is Really Defective

Capability Indices

Compare Measurement Error To Process Variability

"How well can we discriminate where in the product distribution a measurement error came from?"



Capability Indices

Compare Measurement Error To Process Variability

SNR = Signal-To-Noise Ratio

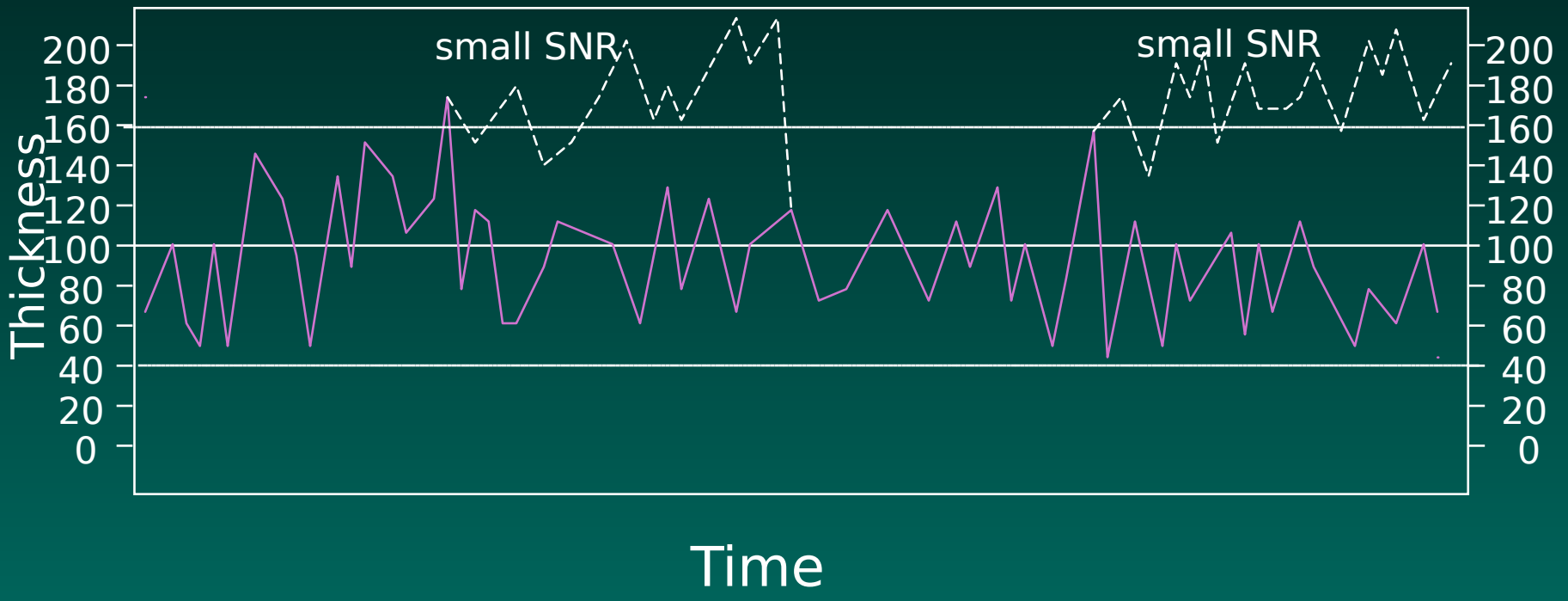
$= \sigma_{product} / \sigma_{ms}$

You want SNR to be big.

Capability Indices

Interpretation of SNR

Small SNR Increases The Time Before An Out-Of-Control Process Is Detected By A Control Chart.



Capability Indices

Typical Target Value for P/T

P/T: <= 0.30

Typical Target Value for SNR

SNR: > 10

Capability Indices

Cautions

- ✓ Poorly developed spec limits imply meaningless P/T.
- ✓ Large P/T does not mean that engineering effort should be expended on improving metrology. The process may be so poor that improving metrology won't help in the short run.
- ✓ P/T and SNR do not indicate where the problem exists in the measurement system (operator, tool, repeatability).

Capability Indices

Caution (cont'd)

- Poor P/T performance may be partially overcome by increasing the sample size.
- Need to look at both P/T and SNR to get the full story.
- Confidence intervals for P/T and SNR can be calculated.